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CHEMICAL ROCKET/PROPELLANT HAZARDS

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VOLUME I

general safety engineering design criteria

JANNAF PROPULSION COMMITTEE

THE JANNAF HAZARDS WORKING GROUP

CHEMICAL PROPULSION INFORMATION AGENCY
THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
Operating under Contract N00017-72-C-4401

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CHEMICAL ROCKET/PROPELLANT HAZARDS

VOLUME I

general safety engineering design criteria

THE JANNAF HAZARDS
WORKING GROUP

NOTICES

The matter contained in this document has been prepared for informational purposes to assist Federal Departments and Agencies in the safe conduct of those activities which involve chemical propellants. The reader is cautioned that the contents have been prepared for use by persons knowledgeable in the technical areas concerned and that such experts need to be duly consulted whenever the contents are to be utilized. The information and recommendations found herein have been compiled from sources believed to be reliable and to represent the best opinion on the subject at the time of preparation. Since these source publications are under continuing revision, the newest revision should be consulted in instances where specific state-of-the-art information is desired by the user.

No warranty, guarantee, or representation, expressed or implied, is made by the Hazards Working Group on behalf of the U. S. Government as to the absolute correctness of sufficiency of any representation contained in this document, and the U. S. Government assumes no responsibility in connection therewith, nor can it be assumed that all acceptable safety measures are contained in this or associated documents, or that other or additional measures may not be required under particular or exceptional conditions or circumstances. The originator(s), in submitting the material is(are) acting in accordance with the requirements of his(their) contract and neither the originator(s) nor the disseminator(s) assumes(assume) any liability to parties adopting any product, process or practice based upon the usage of the information herein contained.

This manual is intended as a source of information and as a guide for the handling, processing, storage and transportation of chemical rocket propellants and ingredients; primary attention is given to the controlled, on-site, situation and circumstances. It is not intended as a regulation concerning the manufacture, storage, use and distribution operations with propellants or propellant ingredients at privately owned facilities. Regulatory bodies and responsible authorities are therefore cautioned against direct application of these guidelines to any specific location or operation without considering the judgement and experience of trained personnel in the areas of concern.

FOREWORD

This volume is intended as a source of information and as a set of basic guidelines for the processing, handling, storage, and transportation of chemical propellants and propellant ingredients. The work was accomplished under the auspices of the Joint Army, Navy, NASA, Air Force Propulsion Committee (JANNAF), formerly the ICRPG, and its Liquid Propellant Subcommittee. The work was managed by the Technical Steering Committee of the Hazards Working Group and performed by the committee members and participants of the Hazards Working Group. The complete work—Chemical Rocket/Propellant Hazards—consists of three volumes, each a task of one or more of the committees as indicated below:

Chemical Rocket/Propellant Hazards

Volume I - October 1971 - "General Safety Engineering Design Criteria," by the Safety Criteria Committee and assisted by all of the committees of the Hazards Working Group.

Volume II - May 1970 - "Solid Rocket/Propellant Processing, Handling, Storage, and Transportation," by the Solid Propellant Manufacturing, Handling, and Storage Committee and assisted by the Committee on Environmental Health and Toxicology.

Volume III - May 1970 - "Liquid Propellant Handling, Storage, and Transportation," by the Liquid Propellant Handling and Storage Committee and assisted by the Committee on Environmental Health and Toxicology.

Volumes I and II both represent a new effort as part of the Hazards Working Group's task to prepare a set of guidelines for use by participants in this expanding chemical propulsion industry. The Liquid Propellant volume represents a complete revision of earlier material which was published January 1963 under the title "The Handling and Storage of Liquid Propellants," Office of the Director of Defense Research and Engineering, Publication No. D4.10:P94/963. It was offered for sale by the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. and is now out of print after a distribution of nearly 10,000 copies. Additional distribution of the same work was accomplished by way of the Department of the Navy, Manual OP-3199 (1 June 1965) and the Department of the Air Force, Manual AFM-160-39 with added environmental health and toxicological data (as Appendix F) by the USAF Medical Service (1 April 1964).

The individual chapters in all three volumes of this work have been reviewed by experienced personnel from industrial organizations and from laboratories and research centers of the three military services and NASA. We now earnestly solicit your comments as users. Comments on the technical content, format, or scope of this work should be addressed to:

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CHAPTER 1

INTRODUCTION

1-1 PURPOSE AND SCOPE

1-1.1 PURPOSE. This publication is intended to provide general guidance, safety criteria, procedures, instructions, precautions, and other related guideline technical information as assistance to those responsible for minimizing the hazards associated with the handling, storage, transportation, and use of liquid/solid propellants.

1-1.2 SCOPE. Information contained in this document has been prepared to assist Federal Departments and Agencies in planning for the safe conduct of activities which involve chemical liquid/solid propellants. Although the use of these guidelines is not necessarily restricted to Government-owned and/or operated facilities, the user is hereby forewarned that the applicability of the information to any specific location, situation or operation depends upon proper interpretati n by experts in the fields of chemical propulsion and safety engineering. The scope of the information is restricted so that the procedures and operations described are those usually undertaken by a military establishment or other Government organization utilizing personnel who have been screened for and trained and certified in an exploratory development and testing program in the field of chemical rocket propulsion. This publication represents an attempt to describe the types of hazards that may be found in processing, handling, transferring and use operations involving chemical propellants and ingredients.

This volume covers General Safety Engineering Design Criteria within the limitations described above. The basic philosophy of medical and environmental factors is explained from the point of view of the environmental health officer or professional toxicologist. The section on Blast, Fragmentation, and Damage is rather fully developed and includes sufficient data and nomograms to the extent that a worker in the field of safety engineering may make quick calculations of fragmentation distance and estimate the damage for a wide variety of situations. A nucleus for successful fire prevention and protection program is provided. Because of difficulties encountered in obtaining and trying to convert such information into usable, meaningful form, it does not contain specific fire-fighting guidelines for each and every propellant and/or propellant combination which is conceivably found in an exploratory development operation. Sufficient information is given on each of the widely used systems and single ingredients so that experienced personnel may estimate certain synergistic effects and develop a plan to cope with the ingredients of a particular system under consideration.

It should be understood by the user of the information contained herein that it is the ultimate responsibility of the supervisory and safety personnel to develop specific written operating procedures and a check list for their facility personnel. It is also their responsibility to see that periodic calibration of detection instruments is performed and logged by qualified personnel.

1-2 BACKGROUND

The preparation of this document involved informal coordination among personnel of the U. S. Army, Navy, Air Force, NASA, other Government organizations, and many of their contractors under the sponsorship of the Liquid Propellant Subgroup of the Interagency Chemical Rocket Propulsion Group (ICRPG) (now JANNAF). The ICRPG Working Group on Hazards, under the management of its Technical Steering Committee, was tasked to develop the information. The Working Group on Hazards has drawn freely from the expertise and information provided by cooperating chemical/rocket propellant and propulsion systems manufacturers, producers and users from the private sector and from local, State, and Federal Government Departments and Agencies.

1-3 APPLICABILITY

This manual is intended as a source of information and as a general guide for Federal and Military Departments and Agencies to assist them in safely conducting activities which involve chemical liquid/solid propellants. It is not intended as a regulation concerning the manufacturing, handling, storage, transferring, distributing or use operations involving propellants or propellant ingredients at either publicly- or privately-owned facilities.

Statements made herein with 'mandatory language'— must, shall or will— and the use of the word 'approved' are meant to indicate a majority and not necessarily unanimous opinion of a group of experts within the area under discussion and they have no regulatory effect unless the cited section is otherwise implemented and made mandatory by DoD, Military or Agency instruction.

1-4 MEDICAL AND ENVIRONMENTAL FACTORS

1-4.1 GENERAL INFORMATION. There are numerous systems of recommendations for evaluating safe concentrations of airborne contaminants. Some of these appear to overlap and this condition can lead to improper application or failure to establish or prescribe a safe working environment. The confusion is bound to become multiplied as new contaminants and circumstances are considered as well as by the entry of additional regulatory agencies into the field. Insofar as each recommended level and system serves a unique and useful purpose, each is desirable; however, unnecessary duplication and the lack of understanding should be avoided at the operational and first line supervisory level.

Personnel working with rocket propellants need to be concerned about two conditions of exposure to atmospheric contaminants. Some materials may be encountered more or less regularly, perhaps continuously, in the working environment. Employees might thus be exposed for eight hours a day, five days a week, for a long period of time. Infrequently, emergencies occur in which a person may be exposed to an atmospheric contaminant at a high concentration for a brief time. Recommendations for safe exposures under these two conditions are provided by various groups of experts. Various instrumental methods for detection of airborne contaminants are described in detail within this work. (See Section 5-7—Hazards Monitoring (Detection of Leaks and Gaseous Effluent) of this volume (I) and Appendix D—Detection Equipment of Volume III.)

1-4.2 DAILY EXPOSURE IN THE WORK ENVIRONMENT. Hygienic standards for eight hour exposure are intended to serve as guides to industrial management in maintaining safe working environments for the selected population of healthy workers. These standards assume an exposure of eight hours per day, five days per week, for an indefinite portion of the employees' working lifetime. They are not intended to be converted by mathematical extrapolation to shorter or longer exposure periods nor are they intended to be applied to a general population.

1-4.2.1 Threshold Limit Values (TLV's—ACGIH). The American Conference of Governmental Industrial Hygienists (ACGIH) annually adopts a list of Threshold Limit Values of Airborne Contaminants and Intended Changes. These are concentrations of contaminants to which it is believed that nearly all workers may be exposed without adverse effect. Most of the values are averages for the eight hour exposure and thus allow for minor fluctuations above and below the TLV. Some of the values are designated as "C" or ceiling values and are not to be exceeded even briefly. Provision is also made for the calculation of TLV's for mixtures of contaminant materials. ACGIH does not consider the TLV's to be appropriate for legislative regulations. These values are the most universally used and are commended to the users of this manual as guidelines. The annual listing may be purchased from the Secretary, ACGIH, 1014 Broadway, Cincinnati, Ohio 45202. (Reference 1)

1-4.2.2 Threshold Limits (Pennsylvania). The Pennsylvania Department of Health under Legislative Article 432 issues "Regulations Establishing Threshold Limits in Places of Employment". These closely resemble the ACGIH—TLV's; however, in addition, the Pennsylvania Advisory Health Board issues regulations for TLV's for materials not included in the ACGIH list. Regular amendments to the regulations are issued which contain additions, revisions, and deletions. Those concerned with these regulations may obtain copies from the Division of Occupational Health, P. O. Box 90, Harrisburg, Pennsylvania 17120. Similar regulations have been issued by other states including Connecticut, Massachusetts, Michigan, New York and Washington. Copies may be obtained from the corresponding state departments of health.

1-4.2.3 USASI Acceptable Concentrations (AC's). The United States of America Standards Institute has established standards for acceptable concentrations for materials which may be encountered in industrial atmospheres. They represent the concentrations of contaminants below which known ill effects or discomfort are unlikely to be experienced by any industrial worker except hypersusceptible individuals. Until recently these have been ceiling values, not averages, and all fluctuations should be below the stated AC value. No provision is made or consideration given to multiple exposures or simultaneous exposure to two or more contaminants. The term acceptable concentration does not refer to a single level for all exposure situations. It is related to the duration and pattern of exposure and the relationship varies between substances. The standards are designed to avoid:

a. Undesirable changes in body structures or biochemistry.

b. Undesirable functional reactions that have no discernible effects on health.

c. Irritation or other adverse sensory effects.

The standards are intended to be used by professionally competent personnel as guides to good industrial hygiene practices. The AC's are not intended to have any legal status nor are they intended to be applied to community air pollution problems. The Z-37 Committee of USASI prepares the standards separately for each compound and they are periodically reviewed, re-affirmed or revised. Users of these standards should obtain the most recent edition from the institute at 10 East 40th Street, New York, N. Y., 10016.

In recent years the Z-37 Committee has given consideration to the need for several boundaries for acceptable exposure conditions within the conventional eight hour work day. They now recommend acceptable concentrations for:

a. Ceiling concentrations for normal fluctuations during the day.

b. A time weighted average for an eight hour day.

c. Acceptable peak exposures for limited duration and frequency beyond the eight hour ceiling.

Details of these considerations were discussed by Dr. D. D. Irish in the open literature. (See References 2 and 3.)

1-4.3 SHORT TERM EXPOSURE LIMITS. The several sources of recommendations for limits on atmospheric concentrations also approach the problem of planning for emergency procedures in the event of an accidental spill or other incident involving propellants.

1-4.3.1 Emergency Exposure Limits (EEL's—AIHA). The American Industrial Hygiene Association (AIHA) publishes guides which review the available toxicity data and present limits for short term exposures of 5, 15, 30, and 60 minutes. These limits are intended for use by experts who can exercise judgment in applying them to a given situation. A single accidental exposure is assumed and the levels are such that reversible toxic effects and discomfort short of actual incapacitation may well occur. Since no margin of safety is used, these levels should not be mathematically extrapolated to other time limits. These EEL's are not intended as guides for day to day occupational health programs but are meant to be used by management in advance planning for emergencies. It should be emphasized that practical use of the EEL's depends upon detection instrumentation that provides unambiguous information about the absolute level of airborne contaminant at the point of contact with the worker. The EEL must be a calibration point for the detection equipment and the behavior of the instrumentation and the performance under actual operating conditions must be known and demonstrated at concentration levels in a span of values which also includes the previously described threshold limit value. The facility supervisor maintains a data record of periodic calibration tests. (Ref.4)

1-4.3.2 Emergency Exposure Limits (NAS/NRC). The National Research Council's Committee on Toxicology has recommended Emergency Exposure Limits (EEL) (formerly designated Emergency Tolerance Limits) for use by military and space agencies. These are intended to be used for the establishment of safe operating procedures. They are to be applied to possible accidental situations which are expected to be rare, single events in the lifetime of an individual. Allowance is made for the increased ventilatory rates of exposed persons but no safety factor is incorporated. The definitions and assumptions are otherwise quite similar to those of the EEL's by AIHA. Likewise, these EEL's are not to be extrapolated to any other exposure times. (NAS/NRC uses only 10, 30, and 60 minute intervals—no five minute interval is recommended.) A detailed discussion of the development of the limits is presented in the Committee's publication. (Reference 5)

1-4.3.3 *Maximum Concentrations (Pennsylvania)*. The Pennsylvania Department of Health under Legislative Article 432 issues "Regulations of Establishing Threshold Limits in Places of Employment". (Reference 6) These regulations include a listing of maximum concentrations to which industrial employees may be exposed for stated periods of time and at stated minimum intervals.

1-4.3.4 Emergency Exposure Limits (USASI). The United States of America Standards Institute has recently adopted the practice of recommending standards for acceptable repeated exposures. For some materials the standards also suggest emergency exposure limits for a single event that will permit recovery or escape without permanent injury. These values, if needed, should be obtained by reference to the most recent specific standard. (Reference 7)

1-4.4 APPLICATION OF THE LIMIT VALUES. With the possible exception of the USASI Standards, all of the TLV's and EEL's are to be applied to a selected population of healthy adults, screened for any hypersensitivity to specific antagonistic agents and subjected to periodic medical examinations. The worker's past history is known to the examining physician and the frequency of exposure as well as the work operation is under the supervision of trained personnel so that even those aspects of the environment can be reviewed and controlled. It cannot be overemphasized that these limits and values are only used in planning operations for use with the population described. No application to the general public is intended nor is it desirable.

1-4.4.1 Limitation of Applicability. Predictable exposures of workers shall be maintained within or below the level specified by the threshold limit values and below those ceiling (C) values specified for certain airborne contaminants. Ventilation, detection instrumentation and personal protection equipment and respiratory devices shall be prescribed by trained supervisory personnel in the form of written operational procedures. In order to obtain the desired control over exposures that will occur it should be obvious that the predictable exposures are very much a function of the site or facility under consideration.

1-4.4.2 Applications. The Emergency Exposure Limits are of prime concern to those responsible for planning emergency procedures in the event of an accidental spill or release of propellants. In particular, the AIHA and NAS/NRC recommendations are applicable. The concepts of the two sets of limits are essentially identical, as are their assumptions and limitations. With one exception their recommendations are the same. This is not surprising since several of the experts are members of both committees. Both sets of values are chosen without any safety factor for individual variability or response and both anticipate that an exposure will be objectionable to the senses and may cause definite effects but it is believed that such exposure will not incapacitate a man either mentally or physically from performing an essential task.

1-4.4.3 Scope of EEL Values. Since the NAS/NRC EEL values are specifically developed as private advice to Federal Departments and Agencies including those concerned with rocket propellants, these values are primarily cited in specific chapters of this work, (the individual propellant chapters in Volume III and the Ingredients Section (3-2) in Volume II). The Committee on Toxicology stresses that these levels are not to be used for predictable exposures of employees, nor for any application to the general public. EEL's must not be confused with a ceiling (C) value or with a maximum allowable concentration (MAC) which is an older and less favored designation for airborne contaminant ceiling values. A recommended EEL, in short, implies no approval for exposing subjects to that level of airborne (or skin contact if it is called out as a specific hazard) contamination. On the contrary, it implies that management bring every resource available to bear upon particular situations such that, by limiting exposure and quantity of material present, by precalculation of diffusion and with advance knowledge of atmospheric conditions, it is possible to protect the individuals under its supervision from any health compromising situations.

1-4.5 AIR POLLUTION CONTROL (NAPCA). According to a statement from the National Air Pollution Control Administration (NAPCA), users of this manual are forewarned that Emergency Exposure Limits or Threshold Limit Values of air pollution toxic substances discussed in this manual are not suitable for application as standards for evaluation or control of community air pollution. It must be assumed that any community located outside the control boundaries of a manufacturing or test site (or any other facility wherein propellant operations take place) is inhabited by some persons of unusually high sensitivity to toxic chemical exposure (e.g., babies, pregnant women, and aged or sick persons). Special precautions must therefore be exercised to assure compliance with all federal, state, or local Air Pollution Control Regulations governing a given location. This is the purpose and policy of the Air Quality Act, as amended (U. S. C. 1857) and of Executive Order 11282, May 26, 1966.

1-4.5.1 Air Quality Control Regions. During 1970 some 57 regions were designated in order to bring all the states within the operating machinery of the Air Quality Act. The regions are named and delineated according to their common area air pollution problems and all states, the District of Columbia, Puerto Rico and the Virgin Islands will be involved with one or more air quality control regions. Local and state entities are responsible for establishing their regional standards with the cooperation of the industries involved. Federal participation in the discussions with local entities and industrial participants is based upon the government agency's authority under the Air Quality Act to decide what pollutants will be controlled and whether the local/state standards are adequate. Local and regional NAPCA office contacts may be made through the local air pollution control district headquarters. As the machinery for a national clean environment becomes more fully implemented, it can be expected that the offices will be well publicized.

1-4.5.2 Air Pollution Alert System. Local and state entities, particularly a local air pollution control center, should be notified upon accidental or imminent uncontrollable release of toxic airborne contaminants. The state police radio net is another possible means of alerting the authorities. It is recommended that departments and agencies work closely with local and state authorities in working out emergency plans and by keeping such authorities briefed on anticipated operations.

1-4.5.3 Emergency Action Plan. After notifying or alerting local authorities the offending facility can then offer its assistance in establishing exclusion perimeters and evacuating persons in the path of released contaminants. Available data for establishing the extent of the hazard should include:

a. The exact nature/behavior and quantity of the pollutant.

b. Meteorological data and concentration/source/intensity/dilution rates based upon those data.

c. Detailed diffusion predictions if available from a well-studied area behavior pattern based upon meteorological observations.

d. Within-the-fence readings from specific toxic agent detectors to establish the all clear time.

e. Recommendations for safety clothing, mask-types and respirators for rescue teams.

According to specific operational practices developed for each facility, it is anticipated that at least one rescue team or buddy will be fully equipped and nearby at a safe distance during actual tests for rescue operation depending on the extent and nature of the hazard involved. As suggested in other portions of this document, for certain toxic propellants and ingredients, specific safety equipment will be placed in designated places of storage for ready safekeeping and in non-contaminated areas. The location of these items and the names of personnel competent in their use should be well publicized among the alert personnel, safety staff and individuals responsible for off-site coordination with local authorities. When and if the facility is called upon for assistance (rescue personnel), the staff can be ready to respond with effectiveness and punctuality. Planning for handling an emergency involves the operator answering the facility telephone, the first line supervisor of the test operation with specific but limited numbers of toxic contaminants, the local fire department, the medical staff, the safety officer, the state police radio net operator, the meteorological support service and the research or facility director. The making and development of plans for emergencies does not have to result in hysteria and bad press notices if time is available to fully develop the local response and support. An emergency without a plan is almost sure to produce poor public relations as well as raise the specter of negligence in our liability to the public.

1-4.6 WATER POLLUTION CONTROL (FWPCA). Insofar as the obligation of rocket propulsion test and launch facilities to maintain water quality is analagous to an industrial plant, coupled with the fact that most if not all such work is done with federal government participation, both the Federal Water Pollution Control Act, as amended, (33 U. S. C. 466 et seq) and Executive Order 11288 may apply.

1-4.6.1 Federal Water Pollution Control Act. As amended, Section 10(a) and (b) quoted below state users of interstate or navigable waters have requirements to reduce or abate water pollution.

a. "Pollution of interstate or navigable waters in or adjacent to any State or States (whether the matter causing or contributing to such pollution is discharged directly into such waters or reaches such waters after discharge into a tributary of such waters), which endangers the health or welfare of any persons, shall be subject to abatement as provided in this Act."

b. "Consistent with the policy declaration of this Act, state and interstate action to abate pollution of interstate navigable waters shall be encouraged and shall not, except as otherwise provided by or pursuant to court order under subsection (h), be displaced by Federal Enforcement action."

1-4.6.2. Executive Order 11288. As stated in Sections 1(3); 4(c); and 4(d) of the Order—"Prevention, Control and Abatement of Water Pollution by Federal Activities"—Federally operated facilities have additional requirements placed upon them with regard to water pollution:

a. Section 1(3) "Pollution caused by all other operations of the Federal Government, such as water resources projects and other operations under Federal loans, grants or contracts, shall be reduced to the lowest level practicable."

b. Section 4(c) "Storage facilities for materials which are hazardous to health and welfare, and for oils, gases, fuels or other materials capable of causing water pollution, if accidentally discharged, shall be located so as to minimize or prevent any spillage which might result in water pollution. Engineering measures to entrap spillage, such as catchment areas, relief vessels, or entrapment dikes shall be installed so as to prevent accidental pollution of water."

c. Section 4(d) "No waste shall be discharged into waters if it contains any substance in concentrations which are hazardous to health."

1-4.6.3 Federal Water Pollution Control Regional Offices. The Federal Water Pollution Control Agency has established rudimentary pollution emergency centers in each of nine regions (encompassing all 50 states, District of Columbia, Guam, Puerto Rico, and the Virgin Islands) to determine the proper course of remedial action by the Federal government. These regional offices, in cooperation with other federal, state, local, and private entities, are available to provide direction and coordination for control and clean up activities. Figure 1-1 presents the regional boundaries and shows the location of FWPCA offices and laboratories.

1-4.6.4 Water Pollution Alert System. The emergency centers described in section 1-4.6.3 should be notified of the occurrence of any spill of propellants which can become a cause or contribution to water pollution. The Regional Office (pollution emergency center) address and other details are given in Figure 1-2. An effective nationwide system for pollution alerting is possible if safety engineers, facility directors and common carriers will take the time to set up their network of communication and cooperation before a spill occurs. The data in Figure 1-2 is of no real value—and is certainly not permanent as to the office addresses—unless everyone associated with a possible source of water pollution knows how to make contact with the various local fire departments, and the State police. Then the resources of the regional centers may be brought to bear on an emergency situation. As in the case of air pollution control, close cooperation with local and State authorities is recommended. (See Section 1-4.5.2.)

1-4.6.5 Emergency Action Plan. It is the obligation of the user/carrier of potentially dangerous chemicals to have a contingency plan for coping with water pollution emergencies. Aside from knowing who to call for help it is imperative that the plan include the following fundamental steps:

a. Containment of spilled materials, if possible, through the use of catchment areas, dikes and lined pits to keep contaminants out of surface and ground waters until such time as it can be removed.

b. Employing suitable methods of inerting, reacting or diluting the contaminants to below the danger level if containment is not possible.

c. Alerting those persons who may be endangered subsequent to the emergency.

d. Notifying local and State officials, the State police net and the nearest Federal Pollution Emergency Center if the accident occurs while the materials are in transit by a carrier or user.

1-4.7 RADIATION PROTECTION. Certain inspection and test operations with rocket motors, cases, engines and components of launch vehicles require the use of X-ray and radio-nuclide sources with various levels of radiation emanating from the equipment. These sources should be identified and marked together with any required exclusion areas and perimeters. It is the obligation of the facility management to insure that no person is exposed to more than the maximum permissible dose equivalent for the work periods involved and that control of areas is maintained so that no one is exposed unknowingly. Operations with high-level radio-active sources, such as Cobalt-60, require protection and security as specified in the operating requirements and statements within the license. These procedures are beyond the scope of this guideline. (Reference 8)

1-4.7.1 Equipment Shielding to Reduce Exposure. X-ray equipment for industrial use may be of mobile or fixed type. Use of mobile equipment in field operations may entail use of equipment without the inherent degree of protection offered by a permanent enclosure. The use of portable shielding may be employed to reduce exposure. Prior to actual radiographic exposure, the barriers should be surveyed with a rate-reading, ionization-chamber type of instrument. A fixed, shielded, radiographic facility usually consists of concrete and/or lead barriers of sufficient thickness to limit exposure levels at one foot from the outside surface of the enclosure, to 10mR in any one hour in an accessible and occupied region, and to 100mR or less in an accessible and normally unoccupied region. The effectiveness of both portable and fixed barriers should be tested in the case of multiple exposures if beam direction, voltage, amperage or attenuating materials are significantly altered. The fixed facility with omni-directional shielding designed for the maximum power of the equipment will obviously require fewer surveys, but even these should be checked routinely. No condition is permanent in an R and D test facility and lead shielding, despite its unwieldy nature, has been known to be relocated.

1-4.7.2 Operations to Reduce Exposure. The source and all objects exposed thereto should be contained within a conspicuously posted perimeter that delineates the area in which exposure can reach or exceed 100mR in any one hour. The perimeter should consist of a rope barrier and radiation signs which can be seen from any avenue of approach. For night-time operations, the area must be adequately illuminated. If exposures require horizontal or near-horizontal beams, the configuration of the posted perimeter must be adjusted accordingly. Whenever possible, exposures should be made with the X-ray beam directed perpendicular to the ground with 1/8-inch lead sheeting underneath the entire primary beam to reduce scattered radiation. A fixed facility will be equipped with reliable interlocks, audible and/or visible warning signals which are activated prior to and during exposure, and provisions for operating the control panel from outside the barrier. The operator should be able to see the entire perimeter of the barrier in a portable or mobile operation and should reposition the power cable to the tube end, the control unit, the object and the portable shield if he cannot—then he should re-survey the area prior to actual radiographic exposure. Either fixed or mobile X-ray equipment must not be left unattended while in operation and must be equipped with a key lock to lock open the power source when

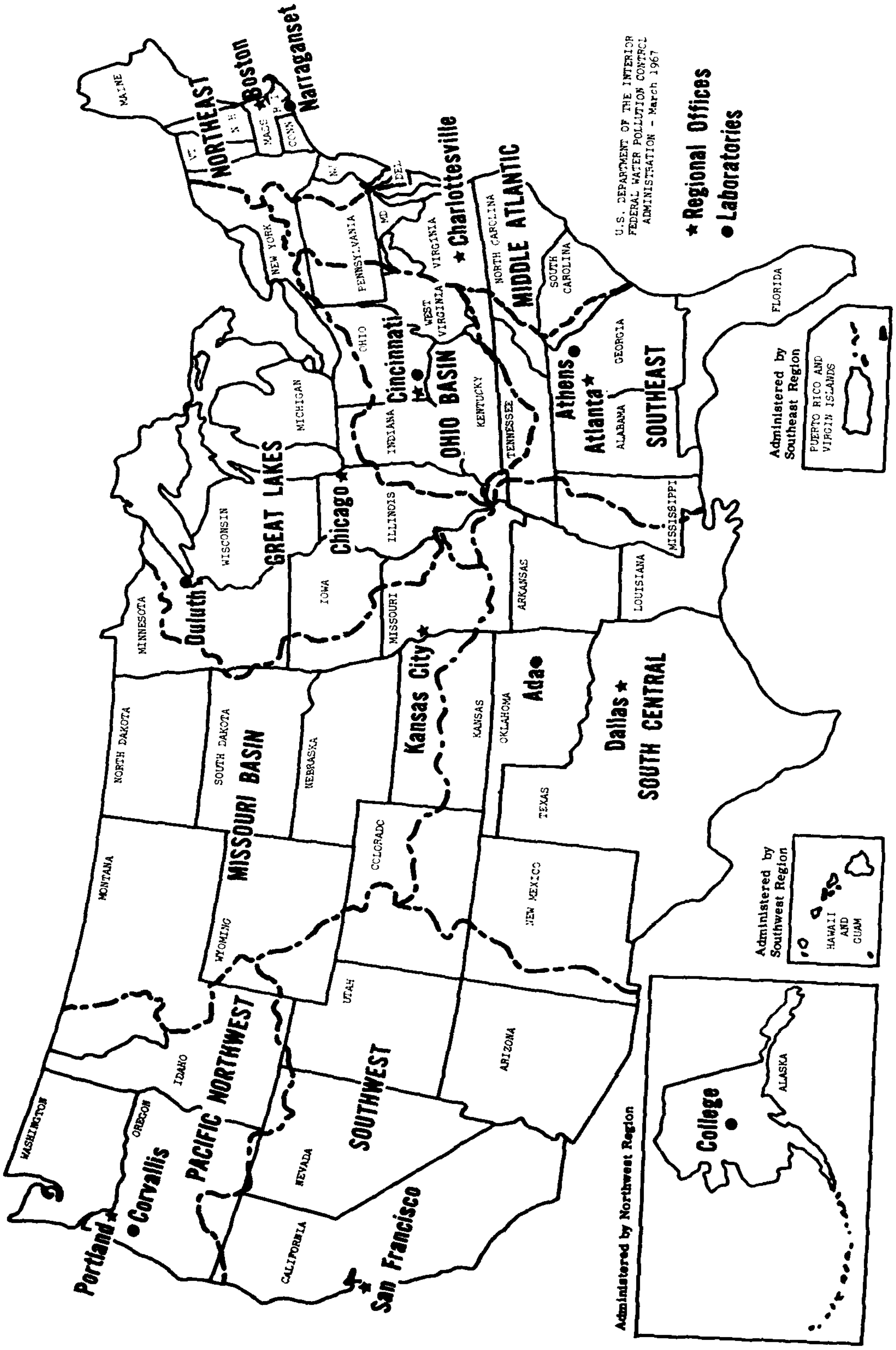

Figure 1-1 Regional Boundaries of the Federal Water Pollution Control Administration, FWPCA (now FWQA)

NORTHWEST

Alaska[3], *California*, Idaho, *Montana*, *Nevada*, Oregon[3], *Utah*, Washington, *Wyoming*

[1]Pittock Block, Rm. 570
Portland, Oregon 97205
(503) 226-3915

GREAT LAKES

Illinois, *Indiana*, Iowa, Michigan, Minnesota[3], *Missouri*, *New York*, *Ohio*, Wisconsin

[1]33 E. Congress Parkway, Rm. 410
Chicago, Illinois 60605
(312) 828-5250

NORTHEAST

Connecticut, Delaware, Maine, Massachusetts, New Hampshire, New Jersey, New York, *Pennsylvania*, Rhode Island[3], Vermont

[1]John F. Kennedy, FOB, Rm. 2303
Boston, Massachusetts 02203
(617) 223-7210

MISSOURI BASIN

Colorado, Kansas, *Minnesota*, Missouri, Nebraska, North Dakota, South Dakota, Wyoming

[1]601 East 12th Street
Kansas City, Missouri 64106
(816) 374-5493

OHIO BASIN

Illinois, Indiana, Kentucky, Ohio[3], *Pennsylvania*, *Tennessee*, West Virginia

[1]R. A. Taft Sanitary Engineering Ctr.
4676 Columbia Parkway, Rm. 115
Cincinnati, Ohio 45226
(513) 871-6200

MIDDLE ATLANTIC

District of Columbia, Maryland, *New York*, North Carolina, Pennsylvania, South Carolina, Virginia, *West Virginia*

[1]918 Emmet Street
Charlottesville, Virginia 22901
(703) 296-1376

SOUTHWEST

Arizona, California, *Colorado*, *Idaho*, Nevada, *New Mexico*, *Oregon*, Utah, *Wyoming*, Guam, Hawaii

[1]100 McAllister Street, Rm. 1802
San Francisco, California 94102
(415) 556-5876

SOUTH CENTRAL

Arkansas, *Colorado*, *Kansas*, Louisiana, *Missouri*, *Mississippi*, New Mexico, Oklahoma[3], Texas, *Tennessee*

[1]Office: 1402 Elm Street
Dallas, Texas 75202
Mailing: 114 Commerce Street
Dallas, Texas 75202
(214) 749-2161

SOUTHEAST

Alabama, Florida, Georgia[3], *Illinois*, Kentucky, Mississippi, *North Carolina*, *South Carolina*, Tennessee, Puerto Rico, Virgin Islands

[1]1421 Peachtree Street, N.E., Suite 300
Atlanta, Georgia 30309
(404) 536-5727

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[1]Address inquiries to: Department of Interior, Federal Water Pollution Control Administration, ATTN: Director or/Estuarine Rep. according to your interest and add regional address as shown.

[2]*Areas of some states are located in several regions due to water shed considerations. See map of Figure 1-1 for location of applicable regional office.*

[3]A Federal Water Pollution Control Administration Laboratory is located in the state.

Courtesy of:

Department of the Interior
Federal Water Pollution
Control Administration
Director, Div. of Tech. Svcs.
Washington, D. C. 20242
(202) 962-4449

Figure 1-2 Regional Offices of the FWPCA (now FWQA) not in operation. The equipment shall be operated only by authorized personnel (radiographer in charge).

1-4.7.3 Monitoring Radiation. Survey instruments vary considerably in their ability to detect low energy rays which form a part of the X-ray machines. Scattered and back-scattered radiation intensities as well as location in the spectrum may vary as well because a variety of materials will be incorporated into the components subjected to exposure. Instrumentation required for surveying should be carefully selected and used accordingly. Rate-reading and ionization-chamber type instruments are preferred.

1-4.7.3 Personal Dosimeters. Prior to commencing radiographic operations, the radiographer in charge should insure that each member of the team has been issued and is wearing two self-reading pocket dosimeters and a film badge while present in and around the radiographic area. Recharged dosimeters should be issued at the beginning of each workday, and shall be read as often as necessary to determine if any excessive exposure to radiation has occurred. The lower reading of the two dosimeters is assumed to be the exposure. If both dosimeters read off-scale, an emergency situation shall be considered to exist, and the individual's film badge shall be submitted immediately for processing.

1-4.7.3.2 Film Badge Dosimeters. A film badge shall be issued on a monthly basis to each person on the team working in and around the radiographic area. Each badge issued shall be worn by only one individual. Control badges are not issued to personnel but remain in the same rack with the badges returned by personnel at the end of each shift and are then submitted with personnel film badges for processing at the month's end. Reports received on processed film badges are reviewed for any unusual or high exposures, and the results are properly recorded on each individual's radiation exposure record which should be maintained (for life) in his medical records.

1-5 HAZARDOUS GAS DETECTION EQUIPMENT

1-5.1 INTRODUCTION. The continuous search for higher performance rockets has resulted in an increased usage of toxic and/or explosive oxidizers and fuels. In order to ascertain safe operation and to prevent damage to personnel or property which might result from leakage of faulty equipment or from exhaust gases, detection equipment is needed which can sense the presence of hazardous vapors below their allowable flammable, explosive or toxic levels. The desired equipment should be simple, sensitive, reliable, rugged, and have adequate range. It also would be highly desirable that it be specific for the vapor to be detected. In the field of automatic detection devices, considerable research and instrumentation development is presently in progress. A variety of different techniques have been developed that are applicable to the detection of oxidizers such as fluorine, halogen fluorides, oxides of nitrogen, hydrazines, hydrofluoric acid, and hydrochloric acid. (See Section 5-7, Hazard Monitoring (Detection of Leaks and Gaseous Effluent) of this volume (I) and Appendix D of Volume III for a discussion of operating principles and other details.)

1-5.2 DISCUSSION. All the detection methods investigated depend upon the drawing of the sample gas into the analyzing cell. This principle requires the establishment of many sample points especially if a large contaminated area is to be covered. Another major drawback of most of the presently available instruments is their inability to discriminate among various propellants or exhaust products. The possible exception is the radiochemical exchange method which would be specific for a limited number of propellants. It is concluded that any detection method that would indicate a specific signature for any gas specie to be analyzed and at the same time eliminate the drawing of individual samples over a wide area would be extremely important advancement of the state of the art. It would also greatly facilitate safety in operations which involve potentially hazardous propellants.

1-6 REFERENCES

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CHAPTER 2

EXPLOSION EFFECTS AND DAMAGE

2-1 INTRODUCTION

In this chapter, some of the blast characteristics of explosions are considered. Consideration is limited to those characteristics and effects which are particularly pertinent and have a direct bearing on damage to a wide variety of targets, to the targets buildings, vehicles, personnel, or other. Information is not presented for close-in, extremely high-pressure conditions and "hard" targets. Rather, data are given on airblast in lower pressure regions and farther distance ranges which span a broad spectrum of damage to the selected targets—from no damage through slight and moderate damage to complete destruction. Because the definition of damage level may be somewhat subjective and may vary in detail from target type to target type, most of the material given is in terms of basic physical parameters of the shock wave, e.g., peak pressure, positive duration, dynamic pressure, and impulse. This type of presentation should provide flexibility to the user in applying the data to new and herein unconsidered situations.

The blast characteristics of explosions are determined by many factors, and vary as a function of these factors. The type of explosive, the medium of burst, i.e., underground, on the surface, or at altitude, the medium of propagation, and even atmospheric conditions influence airblast. These elements of the problem are all considered in some depth in the succeeding sections of this chapter.

Although this volume is intended to consider the hazards and effects of rocket propellant accidents and explosions, most of the information in this chapter is given in terms of explosions of solid high explosives (HE). This approach is used for two reasons: one, there is a dearth of explosions effects information on propellant explosions, and two, HE data when properly applied can serve as a basis for predicting rocket propellant (or any other explosive) explosion effects. However, as discussed later herein, considerable care must be applied in using data compiled from condensed High Explosives to low "energy density" or distribution explosives.

Airblast interactions with targets and target response, i.e., damage, are also discussed. There is such a large number of target types and so much variation in important structural details within any target type that only a generalized approach is presented, mainly in the form of tables and graphs, in Section 2-7. In addition, the information presented in Section 2-7 discusses the basic approach to blast-target interaction and indicates the use of the phenomenological blast data given in other sections of this chapter. This should provide a guide to detailed analysis of target vulnerability and response for any specific target/explosion situation.

Because man is a particularly important possible target, a rather detailed section deals with the hazards to personnel from blasts and fragments.

Fragmentation of cased charges and fragments resulting from target material are briefly considered. Here, more than in the other areas covered, there is a scarcity of information. As new information is developed, it will be incorporated into appropriate handbooks and data sheets or revisions.

In summary, the chapter presents information on blast characteristics as they are influenced by explosive type and weight, geometry of burst, and medium of propagation. It considers the blast parameters as loading functions—inputs—to targets of various types so that the response of these targets may be determined either in a gross fashion or in considerable detail. A brief discussion is presented regarding the general rationale applied in application of data contained herein, typically anomalous situations which may arise in application of this material, and special problem areas and representative approaches to their solution. Although the basic data and the techniques used to extend the applicability of the data are believed to be the latest available, considerable research effort is continuing in the field throughout the country. Updating and extension of the data and techniques will undoubtedly occur and the conduct of special tests and studies to improve these criteria should be included.

2-2 CHARACTERISTICS OF EXPLOSIVES AND EXPLOSIONS

An explosion can be defined as the very rapid release of a very large amount of energy in a very small space. Usually the explosion process is accompanied by the generation of a large volume of gas at high temperatures. The more rapid the release and the greater the available energy, the more violent is the explosion. Some chemical compositions, e.g., TNT, are designed to explode or detonate; others, e.g., propellants, are designed to release energy over longer periods of time. However, under certain conditions, usually unexpected and controlled, propellants may release their energy at a faster rate than normal, that is, they may detonate (explode). In similar unexpected manner, high explosives may not explode "high order" with their full violence; they may explode "low order," deflagrate (burn rapidly), or simply burn at a slow rate.

In this chapter, we are dealing with the mechanical effects of the explosions where only the high order detonation of HE is considered; and for propellants, the most violent chemical reactions leading to detonation or deflagration are considered.

When the explosion occurs most of the available energy in the explosive is converted into some form of mechanical energy. This energy manifests itself in airblast, fragmentation of structural material around the explosive charge, and cratering if the charge is in, on, or near to the earth's surface. These explosion effects are the damage mechanisms of concern. The remaining portion of the explosive energy remains in thermal form and is of concern because of its fire potential.

2-3 TNT EQUIVALENT WEIGHTS

In a general discussion of the effects of explosions, it is often useful to relate the effects of a particular explosive such as TNT. Then, only a single set of data, that for TNT, need be presented to describe the effects of any other specified explosive. This approach is used in this chapter: most data presented are for TNT and tables of equivalent weights relate TNT to other explosives. Considerable caution should be used in the application of so called "TNT equivalencies," to propellants as discussed later herein.

2-3.1 EQUIVALENT WEIGHT DEFINITION. The free-air equivalent weight (EW) of a particular explosive is the weight of a standard explosive, e.g., TNT required to produce a selected shock wave parameter of equal magnitude to that produced by a unit weight of the explosive in question. For valid comparisons the test and standard explosives should have the same geometry or consideration should be given to the effect of geometry on the comparison being made. A given explosive may have several equivalent weights, depending on the shock wave parameter selected, i.e., it has an equivalent weight based on peak overpressure, another based on positive impulse. Table 2-1 defines the abbreviations used in this section.

Table 2-1
Liquid Propellant Nomenclature

Acronym	Propellant
LH_2	Liquid Hydrogen
LO_2	Liquid Oxygen (LOX)
N_2H_4	Hydrazine
IRFNA	Inhibited Red Fuming Nitric Acid (FNA)
JP-4	Hydrocarbon Fuel - Jet
UDMH	Unsymmetrical Dimethyl Hydrazine
RP-1	Hydrocarbon Fuel - Rocket
H_2O_2	Hydrogen Peroxide (HP)
N_2O_4	Nitrogen Tetroxide ($N_2O_4 \leftrightarrow NO_2$ equil.)
TNM	Tetranitromethane

2-3.2 LIMITATION OF THE EQUIVALENT WEIGHT CONCEPT. Strictly speaking, the equivalent weight of an explosive for any given blast parameter varies as a function of the distance from the charge, i.e., the pressure-distance curve for explosive X is not necessarily parallel to that of TNT. For many purposes it is sufficient to cite a single EW number—the average of EW's over some range of pressure. This approach is used here for solid explosives (including propellants); the equivalent weights are the averages obtained over a pressure range from 2 to 50 pounds per square inch (psi).

The single number approach is used also for liquid propellant-TNT equivalence. However, it is important to note that this approach is used primarily because of the scarcity of available data. There are indications on the basis of theoretical work and some few test results that at distances at which the pressure levels over approximately 15 psi, and LO_2-LH_2 explosion, for instance, has a TNT equivalence in terms of peak pressure of about 0.07, from 15 psi to 0.1 psi an equivalence of about 1, and below 0.1 psi it is about 2.0 (reference 1). Interpreting these numbers means that at the 15 psi and above region it takes about 14.3 lbs of LO_2-LH_2 to generate the same pressure distance relation as does 1 lb of TNT, about 1 lb of LO_2-LH_2 to give the same pressure-distance curve between 15 psi and 0.1 psi as does TNT, and only 1/2 lb of LO_2-LH_2 to give similar results as 1 lb of TNT at pressure levels less than 0.1 psi. These equivalent weight numbers indicate also that maximum pressures as high as TNT are not developed by LO_2-LH_2 explosions and that the LO_2-LH_2 chemical reaction is of long duration relative to the TNT explosion. Unless window breakage is of primary importance, the equivalent weights given in Table 2-2 can be used as a conservative representation of propellant equivalence to TNT. Since the test results on which Table 2-2 are based have indicated wide ranges of "TNT equivalency" for liquid propellants, depending more on their degree of mixing, and rapidity of mixing prior to initiation, than on their composition, great care should be used in across the board application of TNT equivalencies to the various liquid propellant systems. (See also Appendix E, Vol. III, this work.)

It should be noted that for most purposes of damage predictions or assessment, small variations in EW are not significant. As indicated in later sections, the distances, at which any given magnitude of most blast parameters of interest occur, vary as the cube root of the weight of the explosive, e.g., an explosive with an EW (for pressure) equal to 1.2 produces any given pressure at a distance only 6 percent larger than the standard TNT. Because the accuracy of measurement of pressure, duration, and so forth is seldom better than 6 percent, and the variability of propellant output in an accident situation can be expected to vary considerably, small variation in EW should be of little concern. For siting and planning purposes, it is suggested that for most cases the maximum EW be used for propellants.

Table 2-3 gives the equivalent weights for solid explosives using peak pressure and impulse as basis for comparison.

2-4 AIRBLAST

2-4.1 AIRBLAST CHARACTERISTICS. One of the major energy outputs of an explosion taking place in the air (or under the surface at small depths of burst) is the airblast. The explosion initially creates a relatively compact volume of high energy gases. The outward expansion of these gases creates a severe, high magnitude (shock) pressure wave which travels initially at supersonic speeds. The front of the shock wave, under ideal "free air" conditions, forms a sphere with its center at the site of the explosion. Immediately behind the front is a region of high velocity, high temperature air flow. At the shock front, the pressure, temperature, and

Table 2-2

Liquid Propellant Explosive Equivalent

Propellant Combination	Other Than Range Launch Pads	Range Launch Pads
LO_2/LH_2	60%	60%
LO_2/LH_2 - LO_2/RP-1	Sum of (60% for LO_2/LH_2) (10% for LO_2/RP-1)	Sum of (60% for LO_2/LH_2) (20% for LO_2/RP-1)
LO_2/RP-1 or LO_2/NH_3	10%	20% up to 500, 000 lbs plus 10% over 500, 000 lbs
IRFNA/Aniline*	10%	10%
IRFNA/UDMH*	10%	10%
IRFNA/UDMH - JP-4*	10%	10%
N_2O_4/UDMH - N_2H_4*	5%	10%
N_2O_4/UDMH - N_2H_4 - Solid*	5% plus the explosive equivalent of the solid propellant	10% plus the explosive equivalent of the solid propellant
Tetranitromethane (alone or in combination)	100%	100%
Nitromethane (alone or in combination)	100%	100%

*These are hypergolic combinations.

Basis: Recommendations of the ASESB Work Group. Tetranitromethane and nitromethane are known to be detonable. (Reference 2)

NOTES:

1. The percentage factors to be used to determine the explosive equivalencies of propellant mixtures at launch pads and static test stands when such propellants are unconfined except for their tankage. Any configurations other than stated above should be considered on an individual basis to determine the equivalencies.
2. The equivalencies of any non-nuclear explosives will be added to the above equivalencies.
3. See Table 2-1 for nomenclature definitions of propellant combinations.
4. Data given herein is undergoing review as of the date of publication. Refer to DoD Manual 4145.27M and current revisions or annexes for latest information. An expanded version of this table is also presented in Volume III, "Liquid Propellant Handling, Storage, and Transportation," Appendix E.

Table 2-3

Equivalent Weights for Free Air Effects[1]

Material[2]	Peak Pressure $(P_M)_{TNT}$	Impulse $(I)_{TNT}$	Composition or Formula
TNT	1.00	1.00	$C_7H_5N_3O_6$
Explosive D	0.85	0.81	$C_6H_6N_4O_7$
Cyclotol 70/30	1.14	1.09	RDX/TNT, 70/30
RDX/5 Wax	1.19	1.16	RDX/Wax, 95/5
Comp B	1.13	1.06	RDX/TNT/Wax, 59.4/39.6/1.0
Comp A-3	1.09	1.07	RDX/Wax, 91/9
Picratol	0.90	0.93	Explosive D/TNT, 52/48
Minol II	1.24	1.22	NH_4NO_3/TNT/Al, 40/40/20
Tritonal 80/20	1.07	1.11	TNT/Al, 80/20
HBX-1	1.21	1.21	RDX/TNT/Al/Wax, 40/38/17/5
Torpex II	1.23	1.28	RDX/TNT/Al, 42/40/18
H-6	1.27	1.38	RDX/TNT/Al/Wax, 45.1/29.2, 21.0/4.7
Pentolite	1.17	1.15	PETN/TNT, 50/50
HBX-3	1.16	1.25	RDX/TNT/Al/Wax, 31/29/35/5
TNETB	1.13	0.96	$C_6H_6N_6O_{14}$
Comp B/TiH_2, 70/30	1.13	1.13	RDX/TNT/TiH_2, 42/28/30

[1]Data are obtained in 2-50 psi range for shock overpressure and converted to EW (see Reference 3).

[2]To calculate equivalent weights not on this table, see Chemical Reviews, Vol. 59, No. 5, 801-825, October 1959.

Table 2-4

Specific Gravity for Soils

Soil Type	Specific Gravity
Dry Clay[1]	1.85
Moist Clay	2.66
Wet Sand	2.64
Alluvium	1.6
Tuff	1.85
Playa	1.6
Rhyolite	2.4
Basalt	2.6

[1]The specific gravity of dry clay may vary between 1.1 and 2.1.

density rise very suddenly to values much greater than the ambient atmosphere and then decay to values lower than ambient conditions, and the air flow will then reverse its direction. Eventually, the pressure density and temperature will return to ambient conditions. See Figure 2-1 for a qualitative description of the above chain of events. This figure also indicates many of the shock wave parameters of particular interest to hazard problems.

2-4.2 GENERAL SCALING LAWS (from reference 4). The generalized scaling laws and correction factors that are used to relate blast parameters for different explosion yields and burst geometries are briefly discussed. The reader may apply this information to those conditions which are not included in the more easily used nomograms and graphs given in the Figures portion of this section. (The information presented in this section pertains to blast effects for static, nonmoving at velocities near sonic at time of burst; a small enhancement in blast effectiveness is realized ahead of the exploding charge.)

2-4.2.1 Cube Root Scaling. Scaling laws are used to calculate the characteristic properties of the blast wave from an explosion of any given energy if those for another energy are known. With the aid of such laws, it is possible to present data for a large range of weights in a simple form.

Theoretically, a given pressure will occur at a distance from an explosion that is proportional to the cube-root of the energy yield. Full-scale tests have shown this relationship between distance and energy yield to hold over a wide range of explosive weights (up to and including a megaton). According to this law, if d_1 is the distance (or slant range) from a reference explosion of W_1 lbs at which a specified hydrostatic overpressure or dynamic* pressure is found, then for any explosion of W lbs, these same pressures will occur at a distance d given by:

$$d/d_1 = (W/W_1)^{1/3}. \qquad \text{(Eq. 2-1)}$$

Cube-root scaling can also be applied to arrival time of the shockfront, positive-phase duration, and impulse; the distances concerned also are scaled according to the cube-root law. The relationships may be expressed in the form $t/t_1 = d/d_1\ (W/W_1)^{1/3}$ and $I/I_1 = d/d_1 = (W/W\ )^{1/3}$, where t_1 represents arrival time or positive-phase duration and I_1 is the impulse for the reference explosion W_1; as before, d_1 and d are distances from ground zero. If W_1 is taken as 1 lb, the various quantities are related as $t = t_1 \times W^{1/3}$ at a distance $d = d_1 \times W^{1/3}$ and $I = I_1 \times W^{1/3}$ at a distance $d = d_1 \times W^{1/3}$.

2-4.2.2 Altitude Corrections. Two conditions are considered: one for bursts at various heights above the surface where the point of observation or interest is on the earth's surface, and two, for bursts at such high altitudes that the atmospheric density variations affect the blast amplitude at co-altitude points of observation.

a. When comparing the blast parameters along the surface from explosions of W lbs at different heights of burst (HOB) in ft, it is necessary to introduce a scaling factor, λ_h with units of $ft/(lbs)^{1/3}$.

$$\text{Scaled HOB} = \lambda_h = (\text{Actual HOB})/W^{1/3} \qquad \text{(Eq. 2-2)}$$

b. For bursts above sea level altitudes, it is required to adjust the blast parameters to account for atmospheric density (pressure) decreases. The general relationships of blast parameters as functions of ambient atmospheric pressure are given by what is called Sachs scaling. For shock pressure, the relationship is:

$$\Delta P_z = P_o\ (P/P_o) \qquad \text{(Eq. 2-3)}$$

where ΔP_z is the blast overpressure at altitude (z) and ΔP_o is that at sea level, and P and P_o are atmospheric pressures at altitude and sea level, respectively. The corrected value of distance for the new overpressure level is then given by

$$d_z = d_o\ W^{1/3}\ (P_o/P)^{1/3},$$

and for arrival time or positive-phase duration at this new distance by

$$t_z = t_o\ W^{1/3}\ (P_o/P)^{1/3}\ (T_o/T)^{1/2},$$

where T and T_o are the temperatures at altitude and sea level, respectively.

For impulse at altitude, I_z, the appropriate relationship is

$$I_z = I_o\ W^{1/3}\ (P/P_o)^{2/3}\ (T_o/T)^{1/2}.$$

Note: The above expressions are applicable when the altitude at the observation point (target does not differ by more than a few thousand feet from that at burst point. If the altitudes do differ considerably, the situation is more complicated (see reference 4). If the altitude of burst is greater than 100,000 ft or 20 miles, these scaling laws are no longer applicable (see reference 4).

2-4.2.3 Spherical Versus Cylindrical Charges. Spherical charges were used to develop a preponderance of existing airblast data. These data may be applied to cylindrical charge explosions, e.g., rocket motors, through the use of a shape correction factor. Figure 2-2 gives this experimentally derived factor (reference 5) in terms of peak pressure ratios for cylindrical charges versus spherical charges as a function of scaled distance (distance divided by the cube-root of the explosive weight).

The charges represented by the band on the figure ranged from 2/1 to 10/1 in length/diameter (L/D) ratio. Note that for large scaled distances, the ratio equals one, i.e., a cylinder produces the same overpressure

*Dynamic pressure $q = 1/2\ \rho v^2$, where ρ is air density and v is particle velocity.

as a sphere of equal weight. The figure is based on pressures measured in a plane normal to the longitudinal axis of the cylindrical charges. At other angles, the pressure ratio is generally less, and in some cases, is less than one. The interpretation of the data is complex, and it is recommended that Figure 2-1 be used for all angles; the pressures in some directions will be overestimated by this procedure and therefore, will be conservative for designing or siting blast-resistant structures. Figures 2-1 through 2-26 follow page 2-9.

Little data exists for positive impulse (the area under the overpressure-time curve at a fixed distance) from cylindrical charges. It is recommended that the peak overpressure correction factors given in Figure 2-2 be applied to positive impulse also. The existing data suggest that this is a conservative procedure.

In summary, then, to determine the blast parameters of an explosion of a cylindrical charge, the procedure is as follows:

a. Calculate TNT equivalent of the cylindrical charge or rocket motor (see Tables 2-1 and 2-3).

b. Using this weight, convert all distances involved to scaled distances.

c. From appropriate figures given at the end of this section, find peak overpressures and impulses at these distances for spherical charges.

d. Find appropriate values of $P_{cylinder}/P_{sphere}$ from Figure 2-1. Multiply overpressures and impulses by these factors as appropriate.

(The use of the recommended correction factors neglects several phenomena known qualitatively to have an effect on the blast wave parameters. The confinement of the explosive (in this case, by the motor wall), the perturbations in the ground reflection effects from those observed with spherical charges, and the point at which detonation is initiated have all been ignored; however, these are second order effects.)

2-4.3 AIR BURSTS

2-4.3.1 Free-Air Bursts (reference 3). The following free-air burst curves cover those situations in which the explosion and the shock wave propagation are in an essentially homogeneous air medium. There are no perturbing influences on the shock because of ground reflections or other discontinuities. Most of the curves are in the form of nomograms covering a large range of charge weights, and the use of each nomogram is illustrated by example on each figure. For conditions not covered by these figures, refer to Section 2-4.2 for the generalized approach to scaling.

a. Peak Overpressure: Figures 2-3 and 2-4 give the peak overpressure at a given distance from a free airburst of TNT at various altitudes. The figures show the pressure for 1 gram to 10^7 lbs of TNT from sea level to 100,000 feet.

b. Positive Impulse: Figure 2-5 presents the positive impulse versus distance and weight of a bare spherical charge in free air. The yield of the TNT charge varies from 10^{-3} to 10^7 lbs.

c. Positive Duration: The positive duration of shockwaves in air versus distance and weight of explosive is given in Figure 2-6. The durations are scaled for yields varying from 1 to 10^7 lbs of TNT.

d. Peak dynamic pressure versus peak overpressure is presented in Figure 2-7 for bare spherical charges in free air. The nomogram gives the pressure for altitudes from sea level to 100,000 ft.

e. Free-air overpressure decay as a function of time is given in Figure 2-8.

f. Figure 2-9 gives the free-air, dynamic-pressure decay as a function of time.

g. The particle velocity versus peak overpressure for bare spherical TNT charges in free air is given in Figure 2-10. By use of the nomograms, the particle velocity can be found for any burst altitude from sea level to 100,000 ft and any temperature from -100°C to +100°C.

h. The shock velocity versus peak overpressure for bare spherical TNT charges in free air is presented in Figure 2-11. By use of the nomograms, the shock velocity may be found for any burst altitude (between sea level and 100,000 ft) and temperature (-100°C to +100°C).

i. Figures 2-12 and 2-13 give the peak reflected pressure (instantaneous reflected pressure) as a function of the peak overpressure for a shockwave striking a rigid surface at normal incidence. By using the nomograms, the pressure may be found for any altitude from sea level to 100,000 feet.

2-4.3.2 Height-of-Burst (HOB). The following curves are for airblast which interacts with the surface. The curves give the pressure, duration, and impulse of the shockwave resulting along the ground from charges exploding at different altitudes above the ground.

a. Peak Overpressure: Figures 2-14, 2-15, and 2-16 give the peak overpressure along the ground surface as a function of the HOB and horizontal ground range for TNT charges in a sea-level atmosphere. (Explanatory material is contained in text for Figure 2-14.) Note that on these figures, bifurcated curves are shown for the relatively low heights of burst. The bifurcation represents the differences in pressure measured on tests where small charges have been used as compared to measurements on large charges. The reasons for the differences are not known at this time. For hazard estimates, it is recommended that the large charge curves by used.

b. Positive-Overpressure Impulse: Figure 2-17 gives the positive-overpressure impulse on the surface as a function of the HOB and horizontal ground range.

c. Positive-Overpressure Duration: Figure 2-18 gives the positive-overpressure durations on the ground as a function of ground range and HOB for a 1-kt burst under sea-level conditions.

2-4.4 SURFACE BURSTS. Explosions of HE charges at the surface of the ground have been categorized into three groups: (a) spherical charges burst half in, half out of the surface; (b) spherical charges sitting on the surface; and (c) hemispherical charges sitting on the surface. The peak overpressure-distance curves generated by these types of surface bursts are sufficiently different to consider them separately.

2-4.4.1 Peak Overpressure. Figure 2-19 gives the peak overpressure as a function of the horizontal distance from ground zero for TNT surface bursts (sphere half buried in the ground) in a sea level (14.7 psi) atmosphere. The curve for charges up to 250 pounds is taken from NOLTR 65-218. The curve for charges of 20 tons and larger is taken from BRL Report No. 1518 At present the reason for the differences between the two curves is not known; for prediction purposes the curve most appropriate to the situation should be used. An average value may be used for yields around 10 tons. For explosives other than TNT, determine their TNT equivalence from Tables 2-1 and 2-3.

The peak overpressure from a spherical charge sitting on the surface may be obtained from Figures 2-14, 2-15, and 2-16 by considering the height-of-burst (HOB) as one charge radius (reference 3).

For hemispherical charges sitting on the surface, Figure 2-20 may be used to determine the pressure-distance relationships.

2-4.4.2 Positive Overpressure Impulse. Figure 2-21 gives the positive overpressure impulse as a function of ground range for a TNT burst in a homogeneous sea level atmosphere. It represents the area under the positive phase of the overpressure time curve at or near the reflecting surface. This curve was scaled from data contained in reference 6.

2-4.4.3 Positive Overpressure Duration. Figure 2-22 represents positive overpressure durations as a function of the ground range for a TNT surface burst under sea level conditions. This curve was scaled from data contained in reference 6.

2-4.5 UNDERWATER AND UNDERGROUND BURSTS

2-4.5.1 Underwater Bursts. Figures 2-23 and 2-24 give airblast pressure along the surface as functions of depth of burst in the water. Figure 2-23 gives data obtained at airblast measuring stations above the water surface at a height of $\lambda y = 0.25$ (scaled height λy = actual height/$W^{1/3}$). The data for Figure 2-24 were measured at a height of $\lambda y = 3$ ft/(lb)$^{1/3}$ (reference 7).

2-4.5.2 Underground Bursts. Airblast data from underground bursts are rather scarce; those which are available show wide scatter for ostensibly the same conditions. A good approach to predicting airblast from underground bursts has been devised and presented in reference 8. The approach is based on an empirical analysis of the data available. Figure 2-25 presents the method; note that the parameters of interest, e.g., yield, soil type, depth of burst, and range, are all combined in an "adjusted ground range, $\bar{X}$" designation. Table 2-4 gives the densities for various soils.

It should be noted that in the experiments upon which the curve of Figure 2-25 was based, there was intimate contact (good tamping) between the charge and the soil. For a charge in a vertical shaft, (effectively at the bottom of a well or silo) not closely coupled to the soil, it is expected that directly over the mouth of the shaft, pressures will be considerably higher than those given in Figure 2-25, with the pressure field falling off at horizontal ranges. Little data are available for this geometry, particularly for pressures outside the shaft. Explosively driven shocktube data, however, would be applicable for guidance (reference 9).

2-4.6 HYDROSTATIC PRESSURE FROM EXPLOSIONS IN ENCLOSED SPACES (References 10 and 11). For a high explosive detonated in a closed air space, a hydrostatic pressure develops within the space subsequent to shock wave propagation. This pressure may be found from the following expression, (derived from the energy equation of state for gas $E = PV(\gamma - 1)$) which gives basically the hydrostatic pressure produced by the burning of a substance in a fixed volume of air without heat loss:

$$\Delta P_o = 4000\ hW/V$$

Where:

h = heat of combustion (kcal/gm)
w = charge weight, lb
V = volume of air, ft^3
P_o = static pressure about ambient, psi

This pressure decays with time as a function of heat conduction and heat convection variables of the container. The above relationship applies to bare charges; static pressures from cased charges will be smaller than those predicted by the equation because of kinetic energy acquired by case fragments.

Table 2-5 gives the heat-of-combustion factor for a number of explosives and Figure 2-26 presents the static pressure plotted versus the volume of enclosed space and the weight of a charge exploded within that space.

Table 2-5

Heats of Combustion Factors for Explosives

Explosives	Heat of Combustion (kcal/gm)
PETN	1.95
RDX	2.28
Pentolite 50/50	2.79
Comp B	2.82
Tetryl	2.93
TNT	3.62
HBX-1	3.73
H-6	3.84
Tritonal 80/20	4.38
HBX-3	4.56

For each material there is some ratio of chamber-volume to charge-weight below which the ambient oxygen concentration is too low to support complete burning of the detonation products. As a result, the full heat of combustion is not realized. When this occurs, static pressures will be lower than predicted by the equation above. The heat-of-combustion values in the table are, therefore, upper limit values (the lower limit being simply the heat of detonation). The range over which this energy transition occurs for individual explosives has not been determined.

Note that since the heat of combustion for any explosive is dependent on the chemical processes taking place during the explosion process, it is appropriate to use the TNT equivalent weights determined for best parameters as heats-of-combustion factors. The heats of combustion given in Table 2-5 are simply standard chemical heats of combustion. Values for any other high explosive or propellant material may be found and used in the same way as are the listed ones.

2-4.7 FINDINGS FROM PROPELLANT TEST PROGRAMS. Several programs have been conducted in order to obtain experimental data which could prove useful for determining the credible damage from assembled propulsion systems. Aside from solid motor hazard classification tests on specific motor packages as performed for the Armed Services Explosive Safety Board (ASESB), there was little data obtained under controlled conditions prior to the 1965-1969 emphasis on test programs. Work is currently underway to analyze the experimental data obtained, to relate it to incidents observed with assembled systems, and to examine the philosophy of using explosive equivalence for establishing a credible damage potential for complex systems of liquid, liquid-solid, and solid rocket vehicles. In addition to the evaluation of the various references cited herein, the reader is strongly urged to obtain and refer to the ASESB documents DOD 4145.26M and DOD 4145.27M together with all their pertinent annexes and revisions. Considerable review effort is in progress with respect to these manuals (references 2 and 12).

2-4.7.1 Project PYRO. This propellant test program and study was conducted in order to develop a more reliable prediction method for estimating credible damage potential of liquid propellant missiles or space launch vehicles. Accidental failure modes during launch or test-firing operations were evaluated. The propellant combinations N_2O_4/N_2H_4-UDMH (50: 50), LO_2/RP-1, and LO_2/LH_2 were examined. The hypergolic N_2O_4/N_2H_4-UDMH system was studied in several configurations and with total weights of 200—1000 pounds of propellants. The second element of the PYRO study included the cryogenic propellants with total weights up to 100,000 pounds and full scale Saturn S-IV and Titan I first stages.

According to experts who reviewed the Project PYRO final report, much valuable peak over-pressure and positive-phase impulse data was obtained. The influence of vehicle (or propellant tank) impact velocity on fall back, missile or vehicle geometry, tank ullage (outage) volume, the total quantity of propellants and other factors were examined in the program and are discussed in detail in the final report (reference 13). A statistical analysis of Project PYRO liquid propellant explosion data was performed by an independent contractor (reference 14) for the Future Studies Office, NASA–Kennedy Space Center. The formal PYRO report highlights the importance of actual ignition time after propellant release, mixing parameters and other factors which control the ignition time. The total energy released was quite variable and a Hazards Working Group PYRO review team strongly urged that a theoretical and statistical evaluation be made of this project together with data from related studies in order to assess the hazards more accurately from pre-launch to the boost phase of a launch.

2-4.7.2 Project SOPHY. This project was conducted with the objective of predicting the hazards associated with the handling, transporting, testing, and launching of solid-propellant rocket motors. It was performed in two phases, SOPHY I and SOPHY II. In the first phase the critical diameter of typical military class II (composite propellants) was determined and then the critical diameter concept was extended to include several propellant grain configurations and to include a determination of the effect of donor intensity, configuration, and location. Critical geometry studies were made to determine the point of partial or complete detonation as a function of these parameters. In SOPHY II initiation criteria were developed with additional critical diameter and critical geometry data points.

The peak side-on overpressure and positive-phase impulse data from 22 tests with PBAN propellant and RDX adulterated PBAN grains. The tests were conducted with grains shaped like right circular cylinders with diameters varying from 11 inches to 72 inches and length of a fixed multiple of four times the diameter. TNT equivalency data is also presented in the final report but the author suggests that further analysis would be required to derive complete information on the TNT equivalency of this type of propellant. This conclusion was supported by the Hazards Working Group review team since they recommended that an analysis of PYRO (see section 4-7.1) should include an evaluation of the SOPHY data for liquid-solid propellant baseline reference on the applicability of the TNT equivalency concept. Details of the work conducted during Project SOPHY may be found in Aerojet-General Corporation technical reports AFRPL-TR-65-211 and TR-67-211, Vols. I and II (reference 15).

2-4.7.3 Other Applicable Propellant Studies. Members of the PYRO review team, Hazards Working Group, suggested that there were several other valuable studies and theoretical works that should be considered for a more complete picture of propellant explosive hazards. Examples cited included:

a. "Prediction of Explosive Yield and Other Characteristics of Liquid Propellant Rocket Explosions," by Erich A. Farber, University of Florida at Gainesville, Florida, NASA Contract NAS10-1255, final report of 31 October 1968. (N69-24207)

b. "Evaluation of Explosive Hazards Criteria and Safety Practices Associated with Titan III Launch Facility Siting, Design, and Operations," by Paul Kennedy, Aerospace Corporation

TOR-0158 (3302)-1, DDC Doc. No. AD 829 728. January 1968.

c. "Size and Duration of Fireballs from Propellant Explosions," J. B. Gayle and J. W. Bransford, NASA TM-X-~~5314~~, 4 August 1965. 53314 (N65-32253)

d. "Liquid Propellant Explosive Hazards," A. B. Willoughby, C. Wilton, and J. Mansfield, URS No. 652-35 or AFRPL-TR-68-92, December 1968. VOL I (AD 855086) VOL II (AD 857342) VOL III (AD 855087)

e. "Pyrotechnics, Hazards Classification, and Evaluation Program," NASA contract NAS8-23524, short title "KEMPOS for NASA/MTF-MSFC," by G. E. - MTSD, Bay St. Louis, Miss., G. E. - MTSD-R-026 and G. E. MTSD-R-030 October and November 1969 resp.

f. "Determination of Explosion Yield of an Exothermic or Detonable Reaction," S. R. Brinkley, Jr., Symposium on Loss Prevention in the Process Industries - Part V, Preprint No. 29(b), New Orleans, La., 16-20 March 1969.

g. "Liquid Propellant Explosions," R. F. Fletcher, Journal of Spacecraft and Rockets, Vol. 5, No. 10, October 1968.

h. "Nitrogen Tetroxide Evaporation—Rate Studies," Chemical Process Laboratory, Edgewood Arsenal, Md., Technical Memorandum EATM2-11-1, (DDC No. AD 488 566), August 1966.

i. "Report of Fragmentation Program," Aerojet-General Corp. for Naval Weapons Laboratory, Dahlgren, Va. on Contract NOrd 18161, AGC No. 0179-64F.

j. "Development of Damage Indexes for Open Frame Structures Subject to Liquid Propellant Explosions," V. M. Conticelli and G. C. Kao, Wyle Laboratories, Research Staff Report No. WR 67-13, May 1968.

k. "Sonic and Vibration Environments for Ground Facilities—A Design Manual," L. C. Sutherland, Wyle Laboratories, Research Staff Report No. WR 68-2 March 1968. (X68-13741)

l. "Preliminary Investigation of Blast Hazards of RP-1/LOX and LH2/LOX Propellant Combinations," J. B. Gayle, C. H. Blakewood, J. W. Bransford, W. H. Swindell, and R. W. High, NASA-MSFC, Huntsville, Ala., NASA TM X-53240, 9 April 1965. (N65-23667)

m. "Project PYRO Dynamic Pressure Accuracy Evaluation," C. M. Richey, Air Force Rocket Propulsion Laboratory, AFRPL-TR-68-111, (DDC Doc. No. AD 693 566), June 1969.

Note: Figures 2-1 through 2-26 follow,
Next text found on page 2-47.

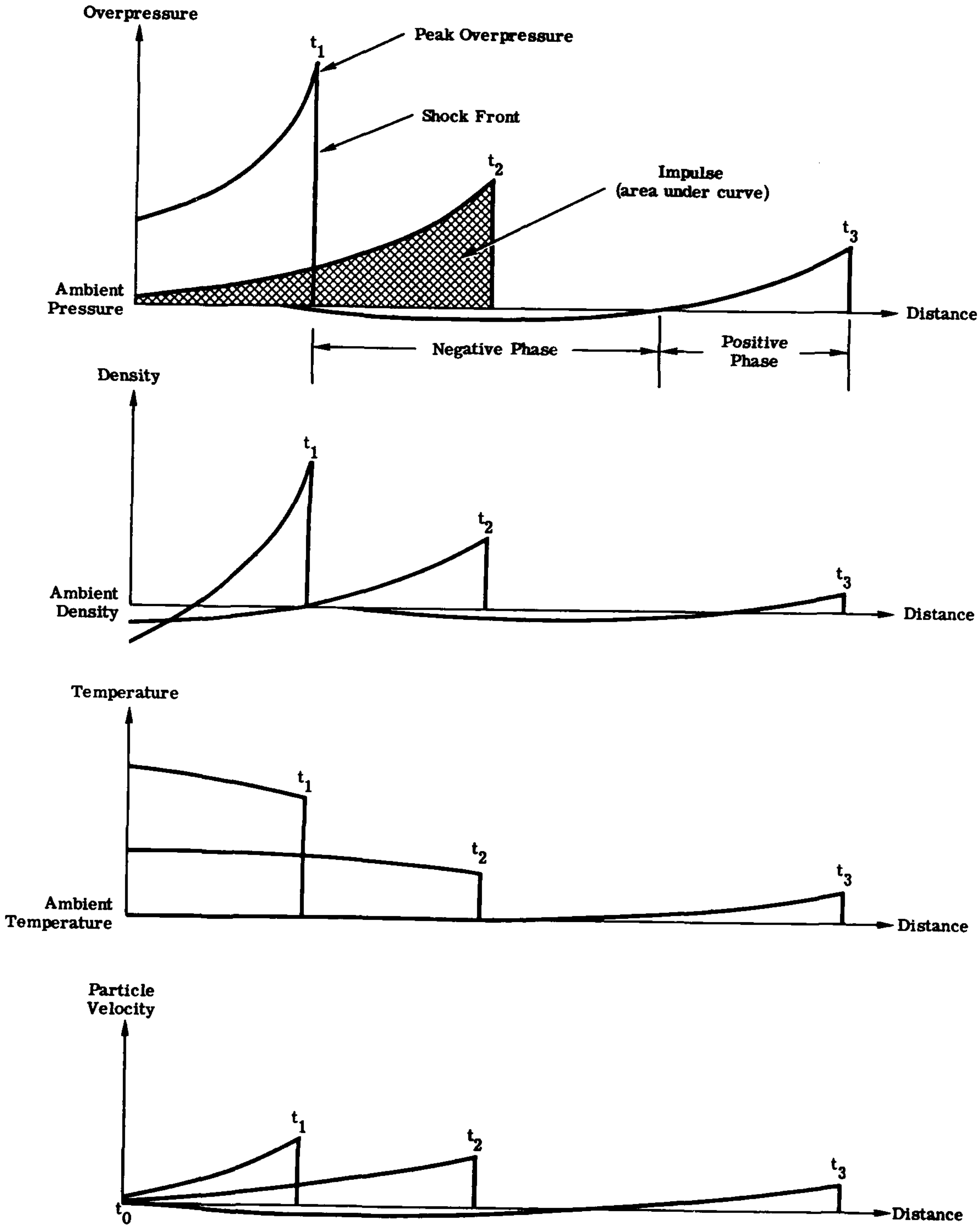


Figure 2-1 Qualitative Variation of Shock Wave Parameters with Distance and Time

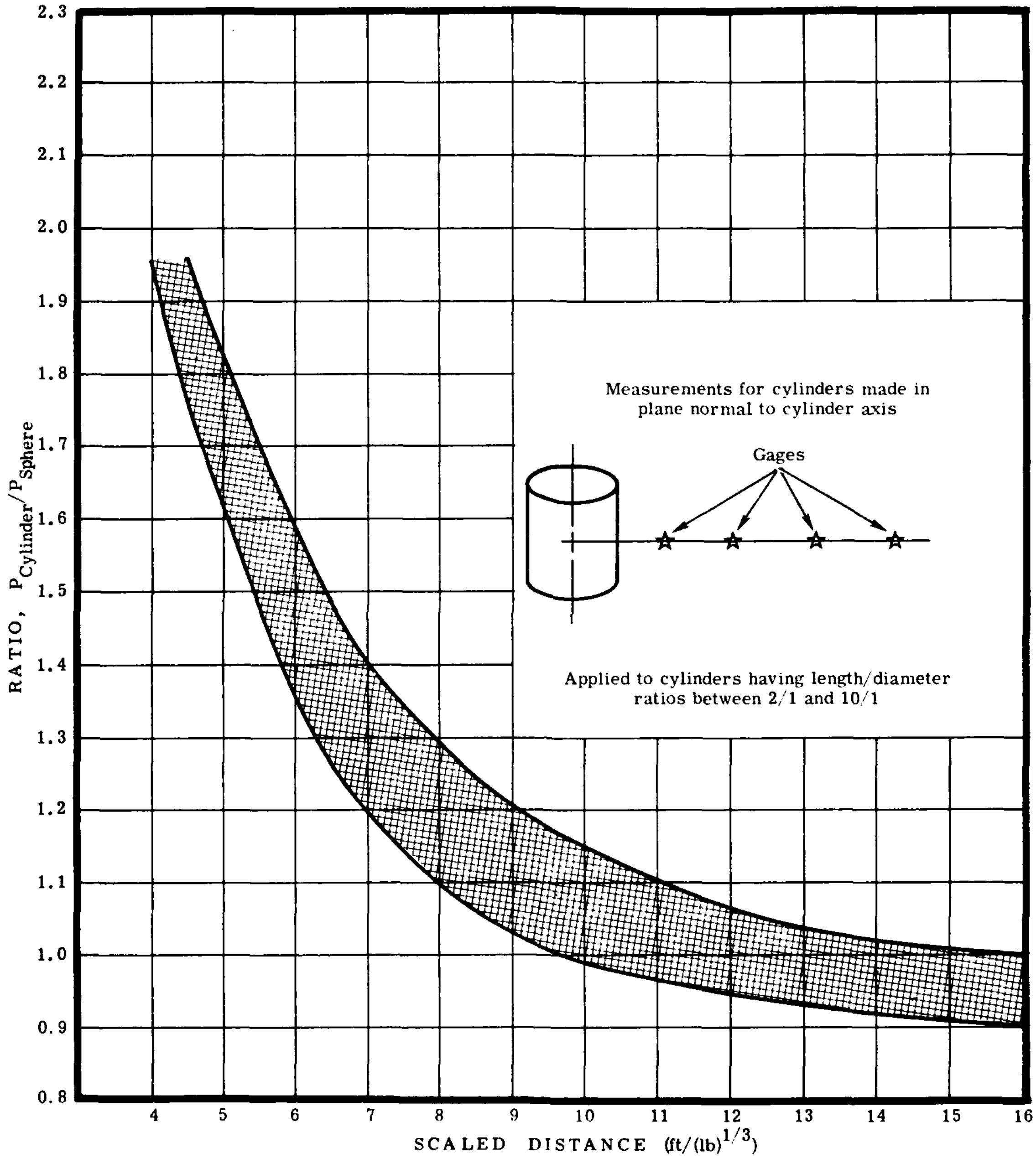


Figure 2-2 Peak Overpressures from Cylindrical Charges Compared to Peak Overpressure from a Spherical Charge of the same Equivalent Weight

Figures 2-3 and 2-4

Free Air Overpressure versus Distance at Various Altitudes

The figures give the peak overpressure at a given distance from a TNT burst in free air at various altitudes as predicted by Sachs scaling (NavOrd Report 2482). The sea level pressure-distance curve is based on the theoretical work of Kirkwood and Brinkley (OSRD-5481) and the experimental work of Weibull (BRL-X-127) and Fisher (NOLM-10780). All three sources are in excellent agreement. For explosives other than TNT, determine their TNT equivalent by multiplying their weight by the peak pressure factors found in Table 2-3.

The effect of altitude on energy release of the explosive is neglected.

The example shows that the peak overpressure at a distance of 30 feet from an 8 pound burst of TNT at an altitude of 90,000 ft is 1.0 psi.

The procedure is as follows:

Step 1 - Connect 8 on the W scale with 30 on the d_z scale and extend the line to λ_z scale; read $\lambda_z = 15$.

Step 2 - At $\lambda_z = 15$ ft/(lbs of TNT)$^{1/3}$ follow parallel vertical lines (values of constant λ_z) to curve.

Step 3 - From intersection point on curve follow horizontal lines (values of constant ΔP_z) to ΔP_z scale; read 1.0 psi.

For additional details see references 16, 17, 18, and 19.

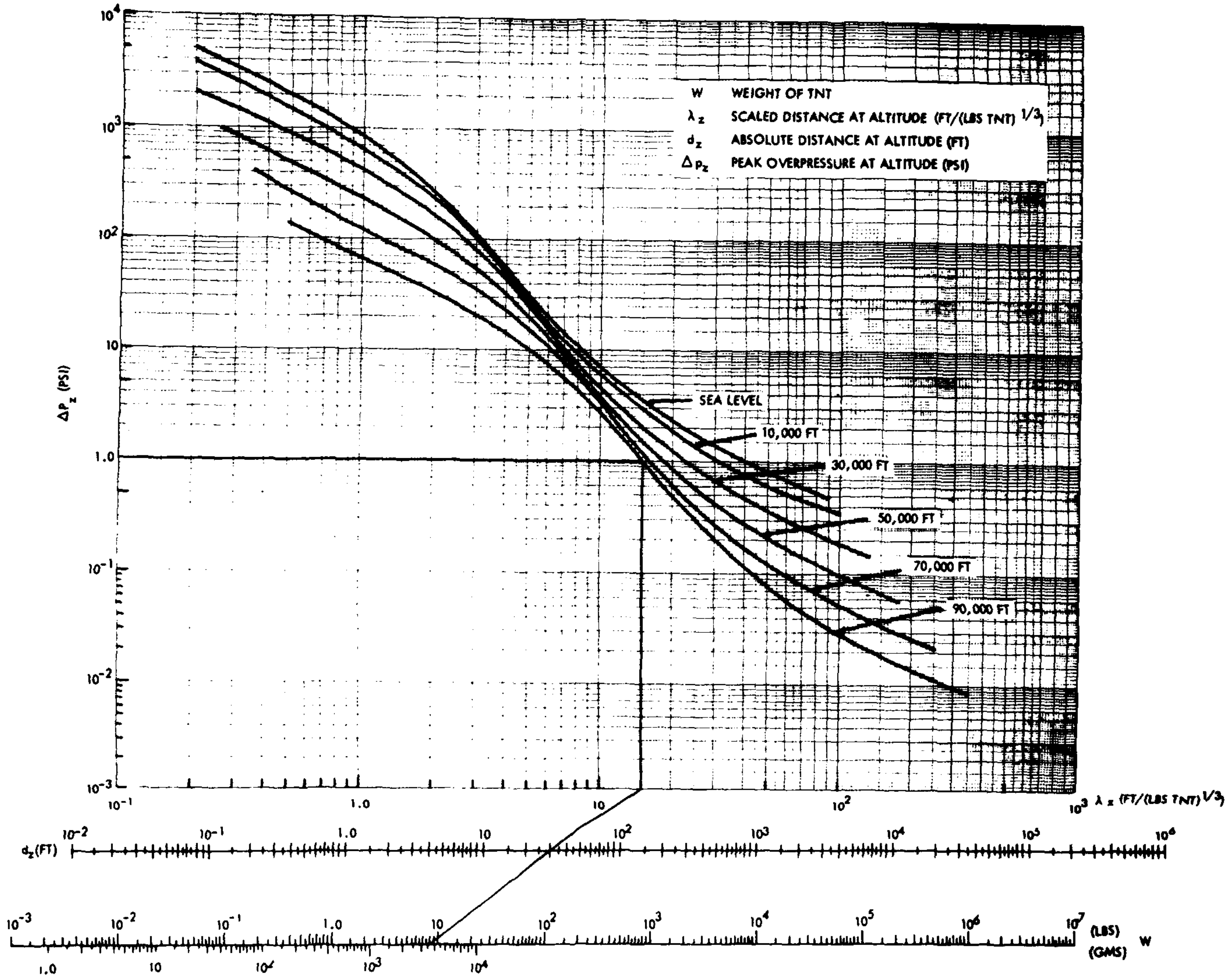
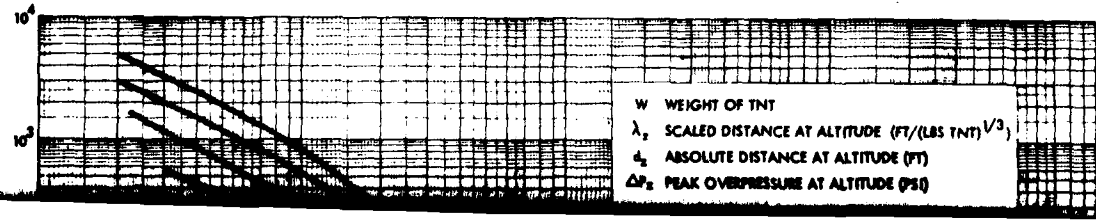


Figure 2-3 Free Air Peak Overpressure versus Distance at Various Altitudes (odd tens of thousands)



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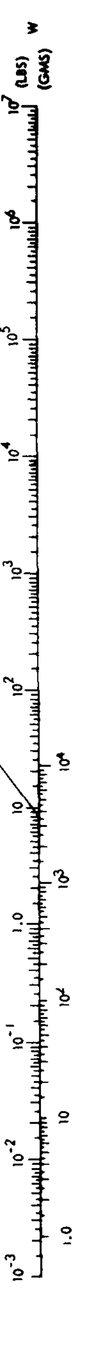

Figure 2-3 Free Air Peak Overpressure versus Distance at Various Altitudes (odd tens of thousands)

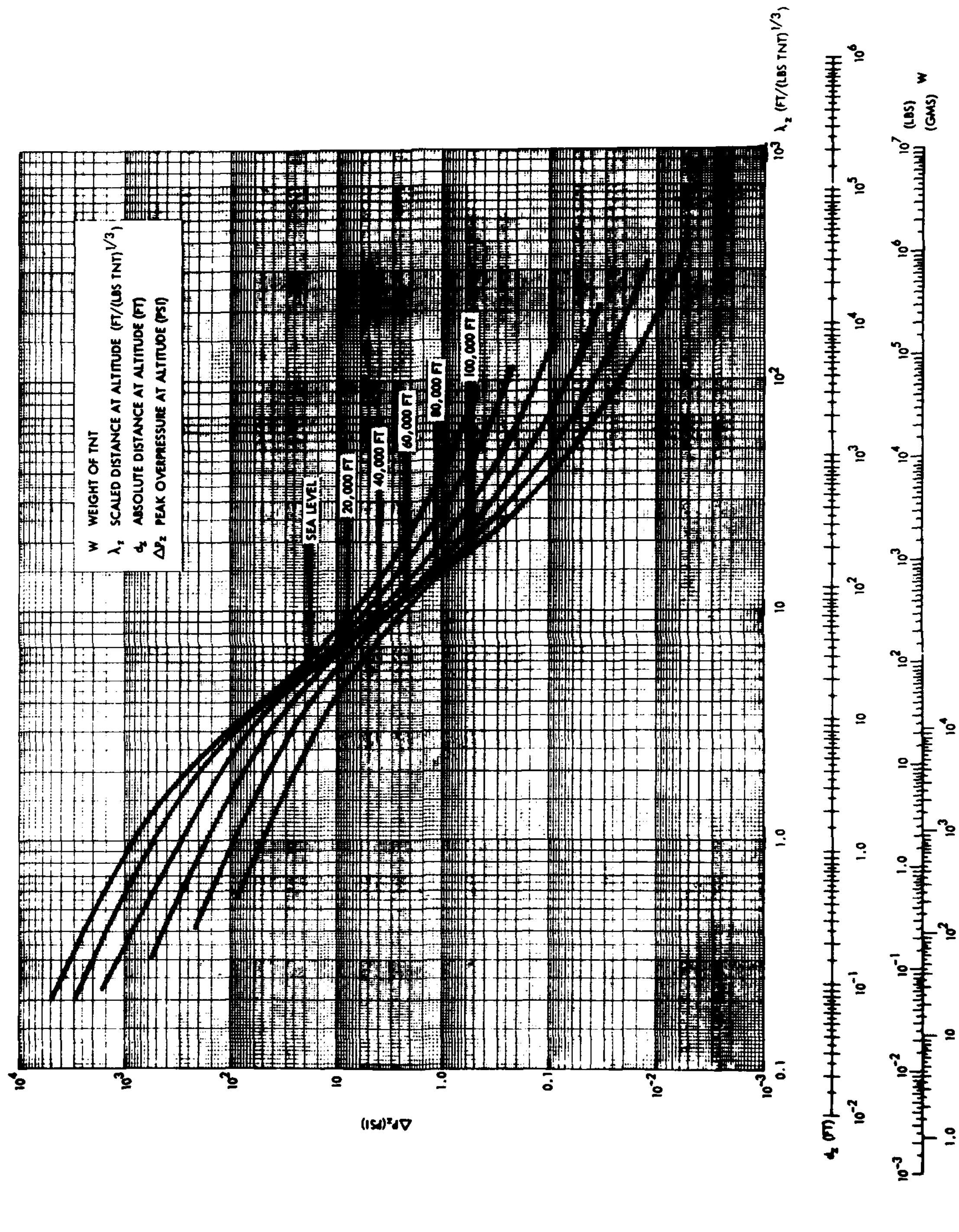

Figure 2-4 Free Air Peak Overpressure versus Distance at Various Altitudes (even tens of thousands)

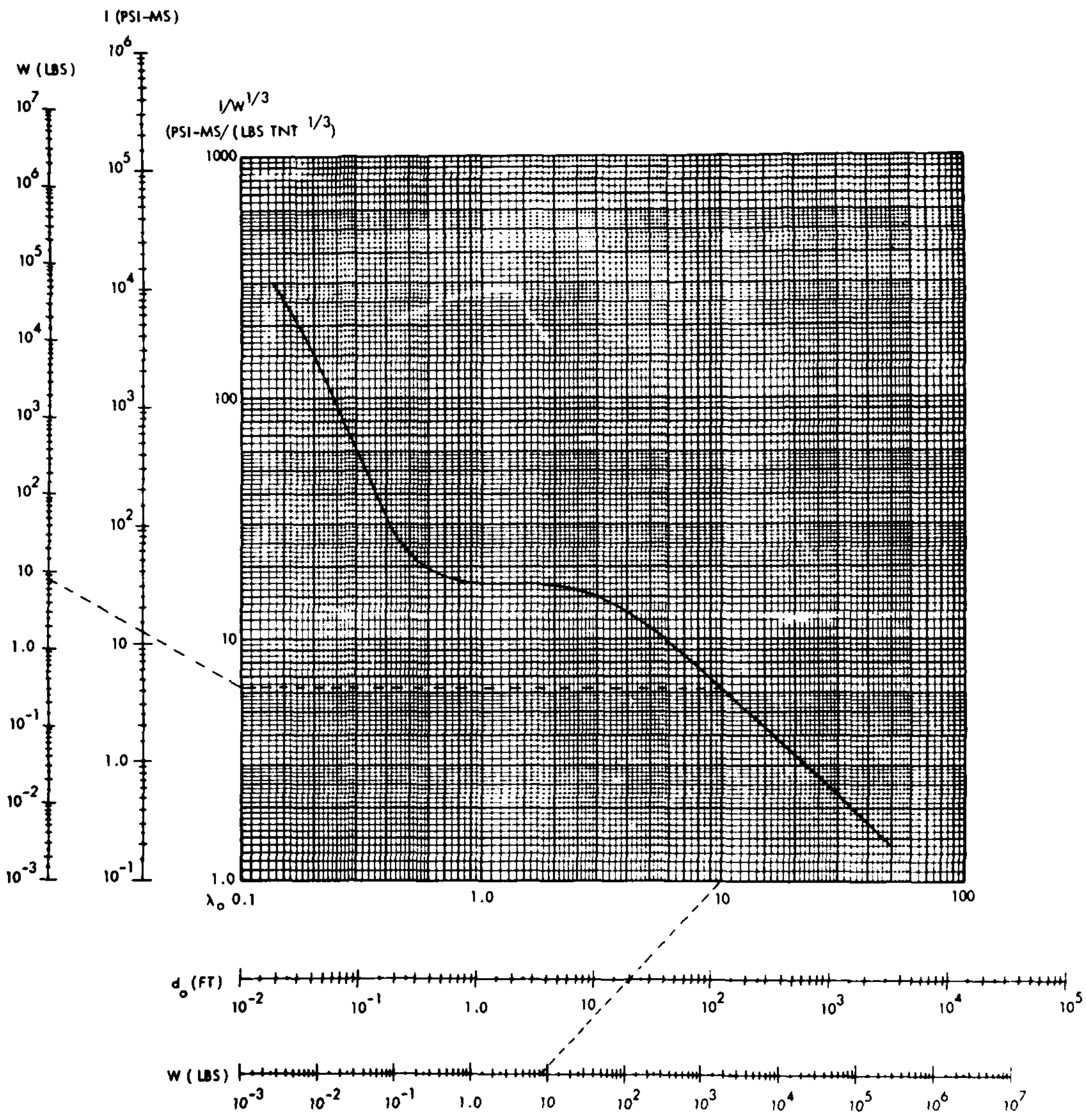

Figure 2-5 Positive Impulse of Shock Wave versus Distance and Weight of Explosive (Reference 6)
(Bare Spherical TNT Charges in Free Air)

Posi

The positive
estimated by det
bare TNT charg
Figure 2-5. The
weight of charge
Table 2-3. For
charges use this

Units:

W = Wei

$I/W^{1/3}$ - Red
per

d_o = Dis

I - Pos

Example:

What is the
(equivalent)

Solution:

Step 1 - Con
10

Step 2 - At λ
valu
curv
valu

Step 3 - Con
rea

2

Figure 2-5

Positive Impulse of a Shock Wave vs Distance and Weight of Explosive (Reference 6)

The positive impulse for explosives other than TNT may be estimated by determining their TNT equivalent (compared with bare TNT charges in free air) and then using the nomograph of Figure 2-5. The TNT equivalent may be found by multiplying the weight of charge by an appropriate impulse factor as listed in Table 2-3. For determining the positive impulse for steel cased charges use this nomograph in conjunction with Figure 2-26.

Units:

W = Weight of explosive in pounds of TNT.

$I/W^{1/3}$ = Reduced impulse, pounds per sq. in. - milliseconds per (pound)$^{1/3}$

d_o = Distance from charge in feet

I = Positive impulse including secondary shock.

Example:

What is the positive impulse of an 8 pound charge of TNT (equivalent) in free air at a distance of 20 feet? (Reference 6)

Solution:

Step 1 - Connect 8 on W scale, with 20 on d_o scale, and read 10 on λ_o scale.

Step 2 - At $\lambda_o = 10$, follow parallel vertical lines (constant values of λ_o) to curve; from intersection point on curve, follow parallel horizontal lines (constant values of $I/W^{1/3}$) to $I/W^{1/3} = 6.3$.

Step 3 - Connect 6.3 (on $I/W^{1/3}$ scale) with 8 on W scale, and read 13 psi-ms on I scale.

EXAMPLE: WHAT IS THE POSITIVE DURATION OF AN 8 POUND CHARGE OF SPHERICAL TNT AT A RADIAL DISTANCE OF 20 FEET?

SOLUTION: STEP 1 - CONNECT 8 ON W SCALE, WITH 20 ON d_o SCALE, AND READ 10 ON λ_o SCALE.

STEP 2 - AT $\lambda_o = 10$ FOLLOW PARALLEL VERTICAL LINES (CONSTANT VALUES OF λ_o) TO CURVE. FROM INTERSECTION POINT ON CURVE, FOLLOW PARALLEL HORIZONTAL LINES (CONSTANT VALUES OF $\tau/W^{1/3}$) TO $\tau/W^{1/3} = 1.94$ ON $\tau/W^{1/3}$ SCALE.

STEP 3 - CONNECT 1.94 (ON $\tau/W^{1/3}$ SCALE) WITH 8 ON W SCALE, AND READ 3.9 MSEC ON τ SCALE.

W = WEIGHT OF EXPLOSIVE IN POUNDS τ = POSITIVE DURATION IN MILLISECONDS

d_o = DISTANCE FROM CHARGE IN FT

POSITIVE DURATION τ IS MEASURED AS SHOWN AT LEFT ON A PRESSURE-TIME CURVE.

POSITIVE DURATIONS FOR EXPLOSIVES OTHER THAN TNT ARE NOT AS YET IN FORM TO BE PRESENTED.

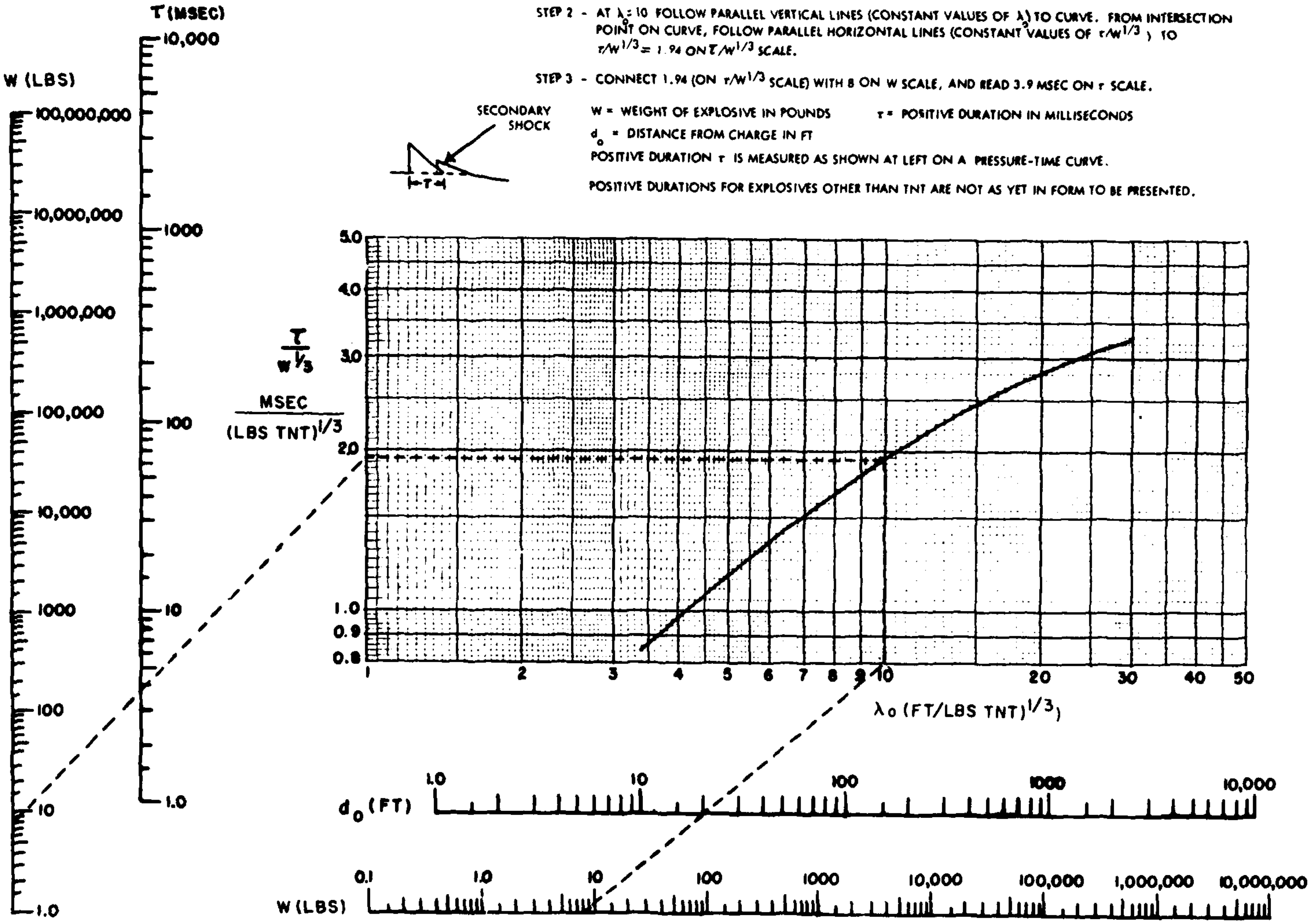

Figure 2-6 Positive Duration of Shock Wave versus Distance and Weight of Explosive (Bare Spherical TNT Charges in Free Air)

Figure 2-7

Peak Dynamic Pressure versus Peak Overpressure
(Bare Spherical TNT Charges in Free Air)

The curve in Figure 2-7 gives the peak dynamic pressure plotted as a function of the peak overpressure as calculated from the Rankine-Hugoniot relation:

$$\Delta q_o = 1/2 \rho_o u_o^2 = 5 (\Delta P_o)^2 / 2 (7P_o - \Delta P_o)$$

where:

Δq_o is the peak dynamic pressure - psi

ρ_o is the ambient density - lbs/ft^3

u_o is the particle velocity - ft/sec

ΔP_o is the peak overpressure - psi

P_o is the ambient pressure - 14.7 psi

By the use of the nomograms, the peak dynamic pressure, Δq_z, as a function of the peak overpressure, ΔP_z, may be found for any burst altitude, Z.

The example shows that at an altitude of 53,000 feet the peak dynamic pressure is 4 psi for a peak overpressure of 5 psi.

The procedure is as follows:

Step 1 - Connect 5 on the ΔP_z scale with 53.0 on the Z_1 scale and extend the line to ΔP_o scale; read ΔP_o = 50 psi.

Step 2 - At ΔP_o = 50 psi, follow parallel vertical lines (values of constant ΔP_o) to curve. From intersection point with curve follow parallel horizontal lines (values of constant Δq_o) to Δq_o = 40 psi

Step 3 - Connect 40 on Δq_o scale with 53.0 on Z_2 scale and read Δq_z = 4 psi on Δq_z scale.

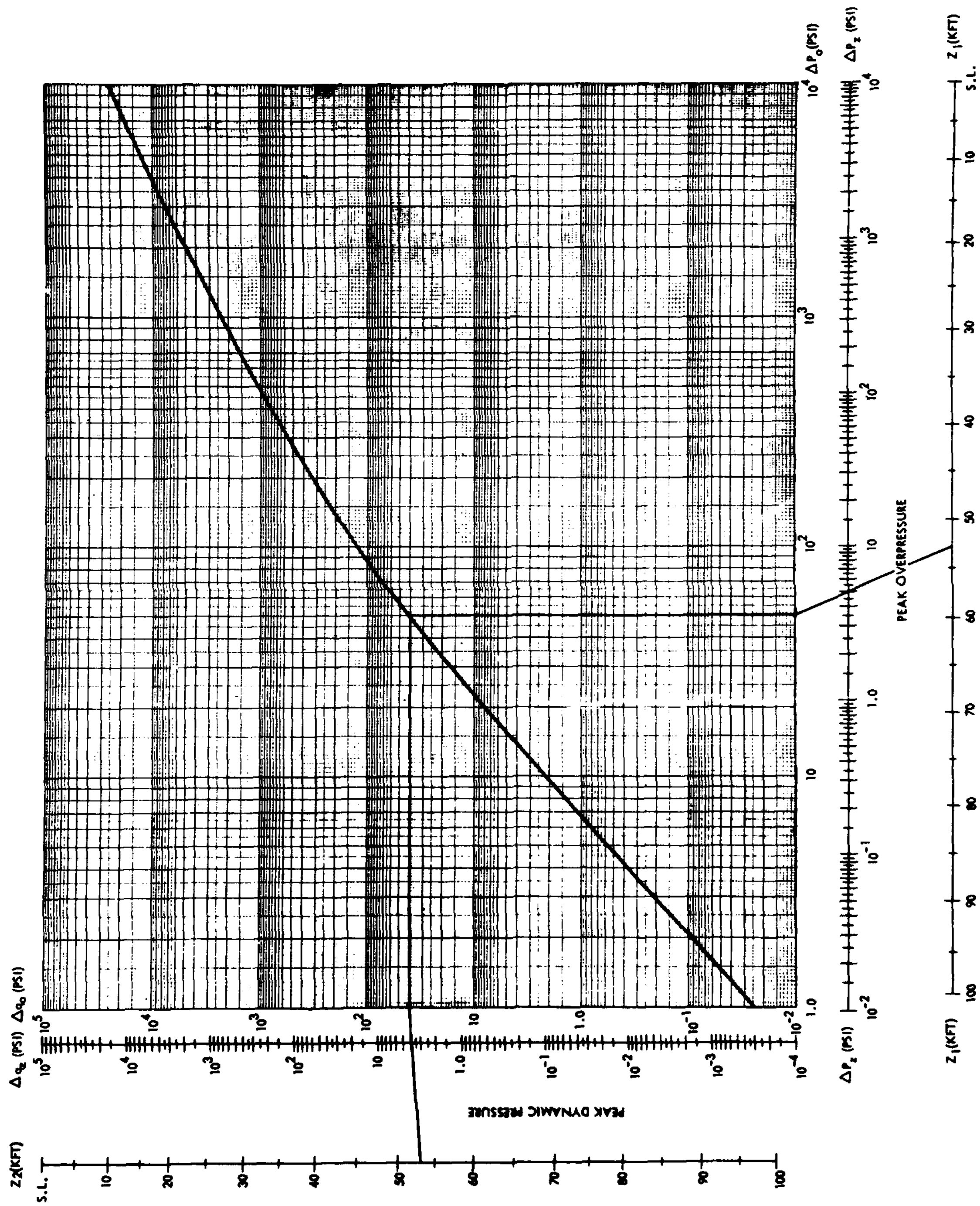

Figure 2-7 Peak Dynamic Pressure versus Peak Overpressure (Bare Spherical TNT Charge in Free Air)

Figure 2-8

Free-Air Overpressure Decay

At a given point in space, the rate of decay of overpressure after shock-front passage depends upon the peak overpressure of the shock-front. Figure 2-8 shows the variation in overpressure with time for various free-air peak overpressures in terms of normalized coordinates; i.e., the overpressure at a given time is expressed as a fraction of the peak overpressure $\Delta P(t)/\Delta P$, and the time is expressed as a fraction of the positive phase duration (t/τ), where $\Delta P(t)$ is the overpressure at the point of interest at a time t after shock-front passage, ΔP is the free-air peak overpressure at the point of interest, obtained from Figures 2-3 and 2-4, t is the time after shock-front passage, and τ is the duration of the positive phase at the point of interest, obtained from Figure 2-6. (Reference 4)

Reliability. These waveforms are based on theoretical calculations for a spherical blast wave propagating from a point source in an ideal gas. These can be used for ideal waveforms at ground surface.

Figure 2-9

Free-A - Dynamic-Pressure Decay

At a given point in space, the rate of decay of dynamic pressure after shock-front passage depends upon the peak dynamic pressure. Figure 2-9 shows the variation in dynamic pressure with time for various free-air peak dynamic pressures in terms of normalized coordinates; i.e., the dynamic pressure at a given time is expressed as a fraction of the peak dynamic pressure $(q(t)/q)$, and the time is expressed as a fraction of the positive-phase duration t/τ_{q^+}, where $q(t)$ is the dynamic pressure at the point of interest at a time t after shock-front passage, Δq is the free-air peak dynamic pressure at the point of interest, obtained from Figure 2-7, t is the time after shock-front passage, and τ_q is the duration of the dynamic pressure phase at the point of interest. The dynamic phase duration τ_{q^+} is assumed equal to the overpressure positive-phase duration τ and obtained from Figure 2-6.

Reliability. These waveforms are based on theoretical calculations for a spherical blast wave propagating from a point source in an ideal gas. They can be used for ideal waveforms at the ground surface.

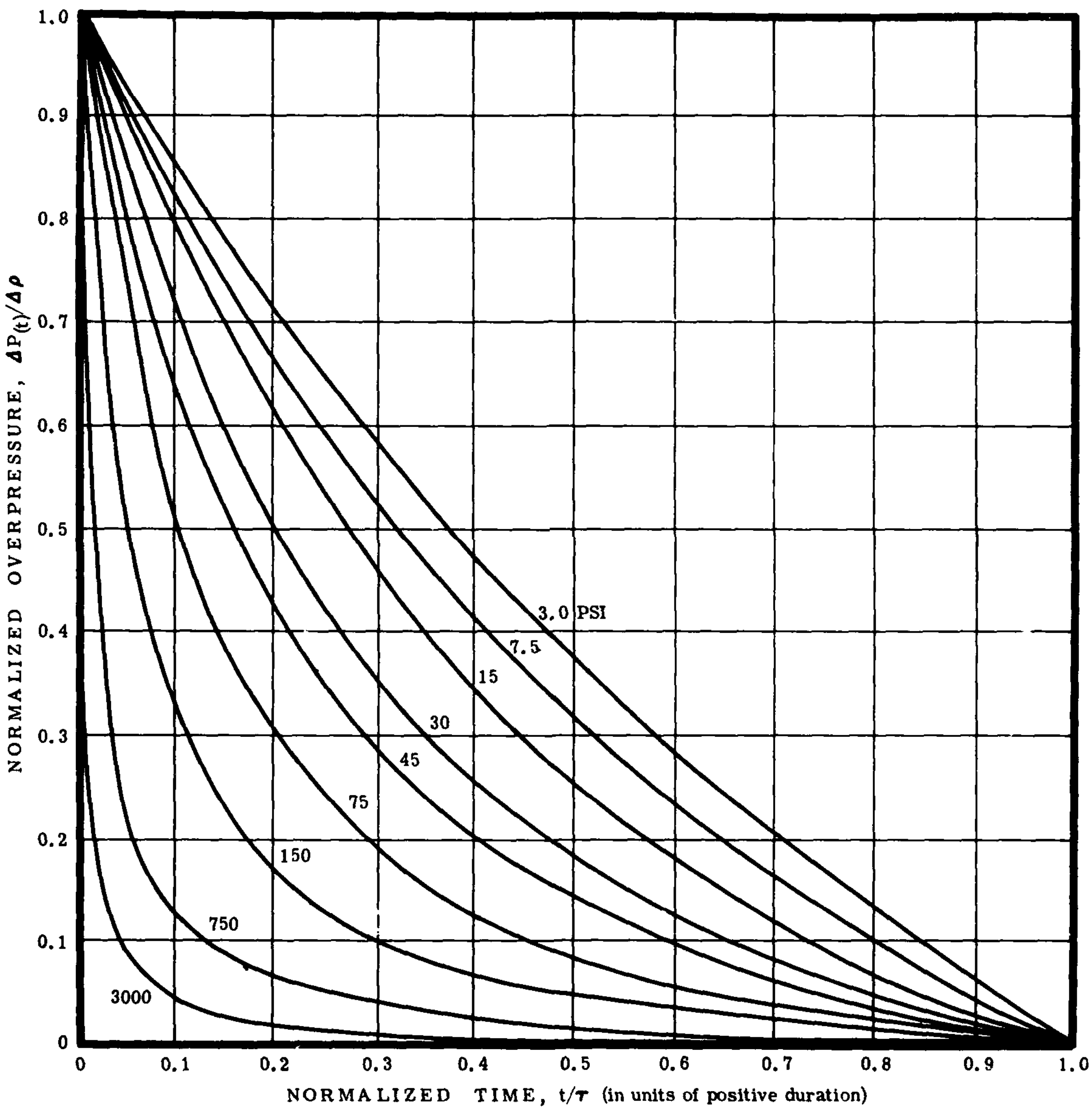

Figure 2-8 Free-air Overpressure Decay

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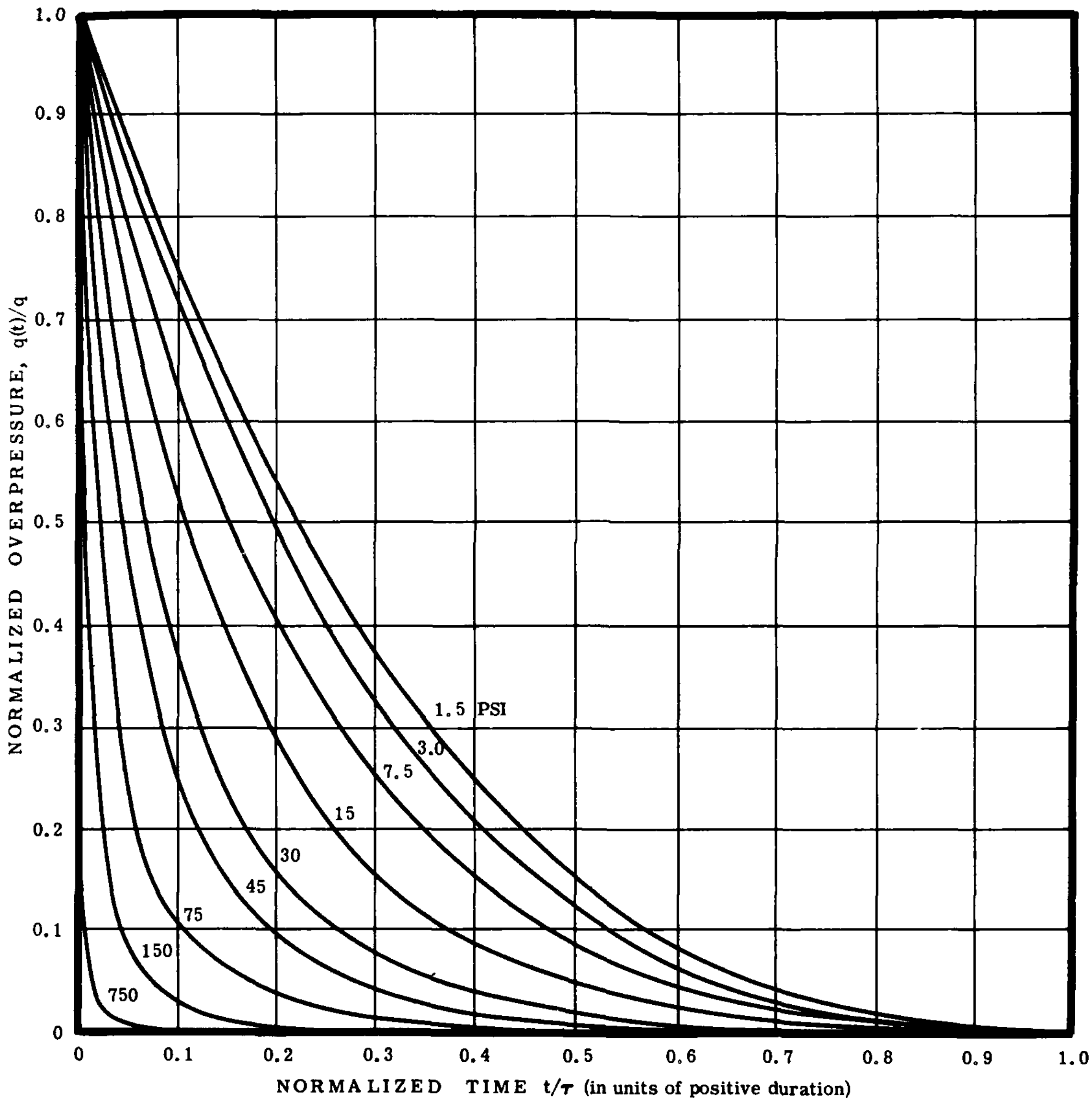


Figure 2-9 Free-air Dynamic Pressure Decay

Figure 2-10

Peak Particle Velocity Behind the Front versus Peak Overpressure (Reference 3)
(Bare Spherical TNT Charges in Free Air)

The curve in Figure 2-10 gives the non-dimensional particle velocity, u_o/C_o, plotted as a function of peak overpressure as calculated from the Rankine-Hugoniot relation:

$$u_o/C_o = 5\Delta P_o/7P_o\ (1 + 6\Delta P_o/7P_o)^{-1/2},$$

and

$$C = C_o\ (1 + T/273)^{1/2}$$

where:

u_o is the particle velocity - ft/sec
C is the sound velocity at some temperature, $T(^\circ C)$ - ft/sec
C_o is the sound velocity at $0^\circ C$ ~ 1087 ft/sec
P_o is the ambient pressure - 14.7 psi
ΔP_o is the peak overpressure - psi

By the use of the nomograms, the particle velocity, u_z, as a function of the peak overpressure, ΔP_z, may be found for any burst altitude, Z, and temperature, T.

The example shows that for a peak overpressure of 50 psi at an altitude of 18,000 ft the particle velocity is 1800 ft/sec when the temperature of the air ahead of the shock is $-40^\circ C$.

The procedure is as follows:

Step 1 - Connect 50 on the ΔP_z scale with 18 on the Z scale and extend the line to the ΔP_o scale, read 100 psi.

Step 2 - At ΔP_o = 100 psi, follow the parallel horizontal lines (values of constant ΔP_o) to curve; from intersection point on curve follow parallel vertical lines (value of constant u_o/C_o) to u_o/C_o scale, read 1.8.

Step 3 - Connect 1.8 on u_o/C_o scale with -40 on T scale and read u_z = 1800 ft/sec on u_z scale.

This nomogram may be used in conjunction with Figures 2-3 and 2-4 to give the particle velocity as a function of distance from a given charge.

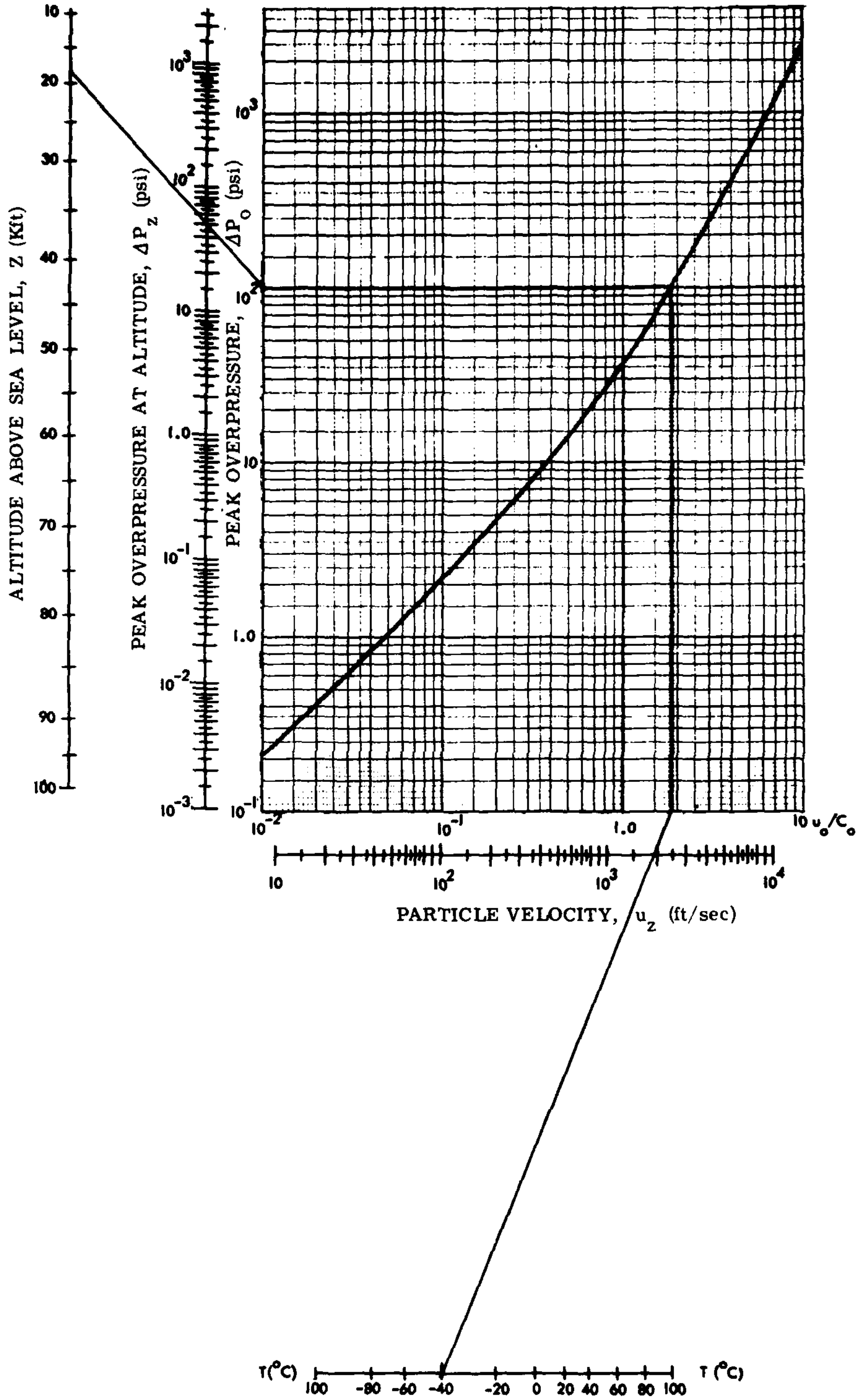


Figure 2-10 Peak Particle Velocity behind the Shock Front versus Peak Overpressure (Reference 3)
(Bare Spherical TNT Charges in Free Air)

Figure 2-11

Shock Front Velocity versus Peak Overpressure (Reference 3
(Bare Spherical TNT Charges in Free Air)

The curve in Figure 2-11 gives the non-dimensional shock velocity,

$$U_o/C_o = (1 + 6\Delta P_o/7P_o)^{1/2}$$

$$C = C_o\ (1 + T/273)^{1/2}$$

where:

U_o is the shock velocity-ft/sec

C is the sound velocity at temperature, $T(^\circ C)$ - ft/sec

C_o is the sound velocity at 0°C - 1087 ft/sec

P_o is the ambient pressure - 14.7 psi

ΔP_o is the peak overpressure - psi

By the use of the nomograms, the shock velocity U_z, as a function of the peak overpressure, ΔP_z, may be found for any burst altitude, z, and temperature T.

The example shows that for a peak overpressure of 90 psi at an altitude of 55,000 ft, the shock velocity is 7600 ft/sec when the temperature of the air ahead of the shock is -40°C.

The procedure is as follows:

Step 1 - Connect 90 on the ΔP_z scale to 55 on the Z scale and extend the line to the ΔP_o scale, read 1000 psi.

Step 2 - At ΔP_o = 1000 psi, follow parallel horizontal lines (value of constant ΔP_o) to curve; from intersection point on curve follow parallel vertical lines (values of constant U_o/C_o) to U_o/C_o scale; read 7.6.

Step 3 - Connect 7.6 on U_o/C_o scale to -40 on T scale and read U_z = 7600 ft/sec on U_z scale.

This nomogram may be used in conjunction with Figures 2-3 and 2-4 to give the shock velocity as a function of distance from a given charge.

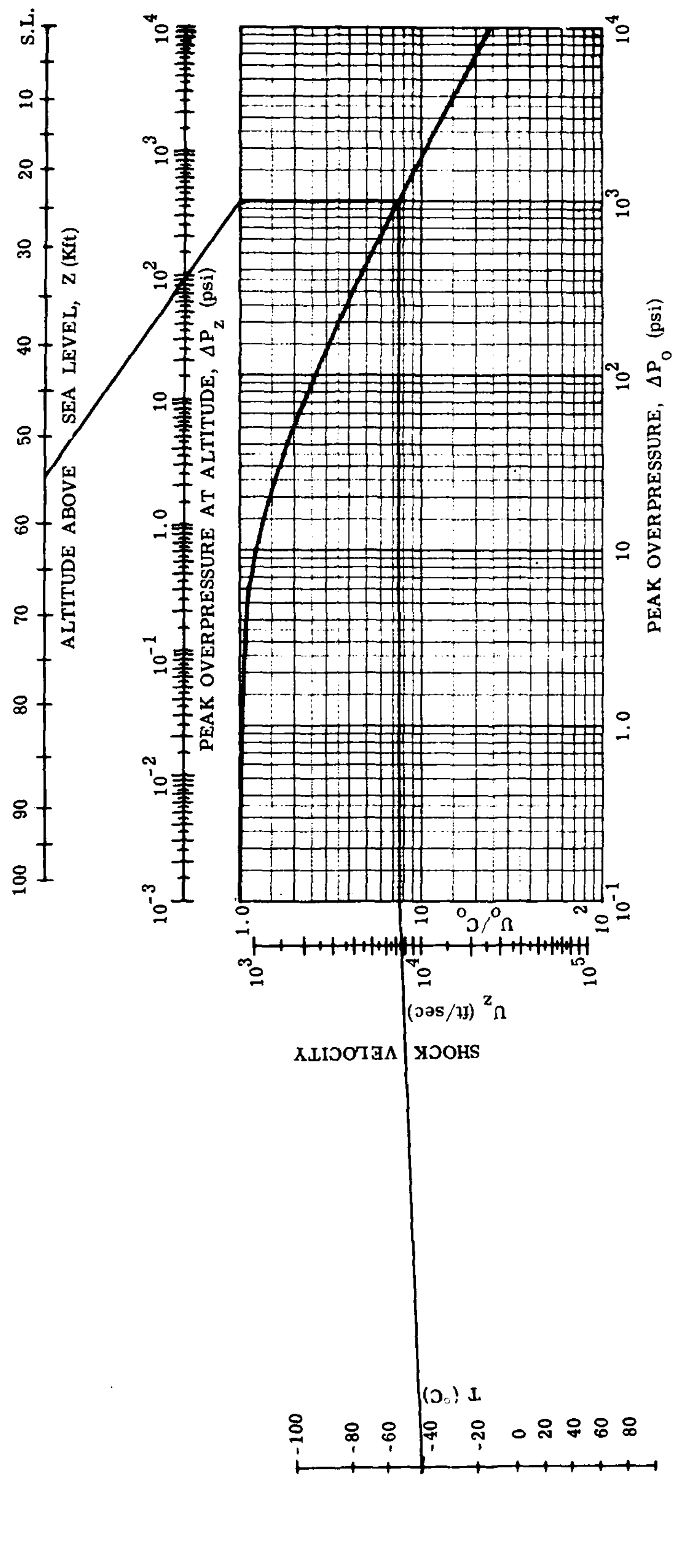


Figure 2-11 Shock Front Velocity versus Peak Overpressure (Reference 3)
(Bare Spherical TNT Charges in Free Air)

Figure 2-12

Peak Reflected Pressure versus Peak Incident Overpressure (Low Range)

The curve in Figure 2-12 gives the peak reflected pressure (instantaneous reflected pressure) as a function of the peak overpressure for shock wave striking a surface at normal incidence. The instantaneous value of the peak reflected pressure is calculated from the Rankine-Hugoniot relation:

$$\Delta P_{ro} = 2\Delta P_o \left[(7P_o + 4\Delta P_o)/(7P_o + \Delta P_o)\right]$$

where:

ΔP_{ro} is the peak reflected pressure - psi

ΔP_o is the peak incident overpressure - psi

P_o is the ambient pressure - 14.7 psi

By the use of the nomograms, the peak reflected pressure, ΔP_{rz}, as a function of the peak incident overpressure, ΔP_z, may be found for any burst altitude, Z.

The example shows that for a peak incident overpressure of 1 psi at an altitude of 18,000 ft the peak reflected pressure is 2.1 psi.

The procedure is as follows:

Step 1 - Connect 1 on ΔP_z scale with 18 on Z_1 scale and extend line to ΔP_o scale; read ΔP_o = 2 psi.

Step 2 - At ΔP_o = 2 follow parallel vertical lines (value of constant ΔP_o) to curve, from intersection point on curve follow parallel horizontal lines (values of constant ΔP_{ro}) scale; read ΔP_{ro} = 4.2 psi.

Step 3 - Connect 4.2 on ΔP_{ro} scale with 18 on Z_2 scale ($Z_1 = Z_2$); read ΔP_{rz} = 2.1 psi on ΔP_{rz} scale.

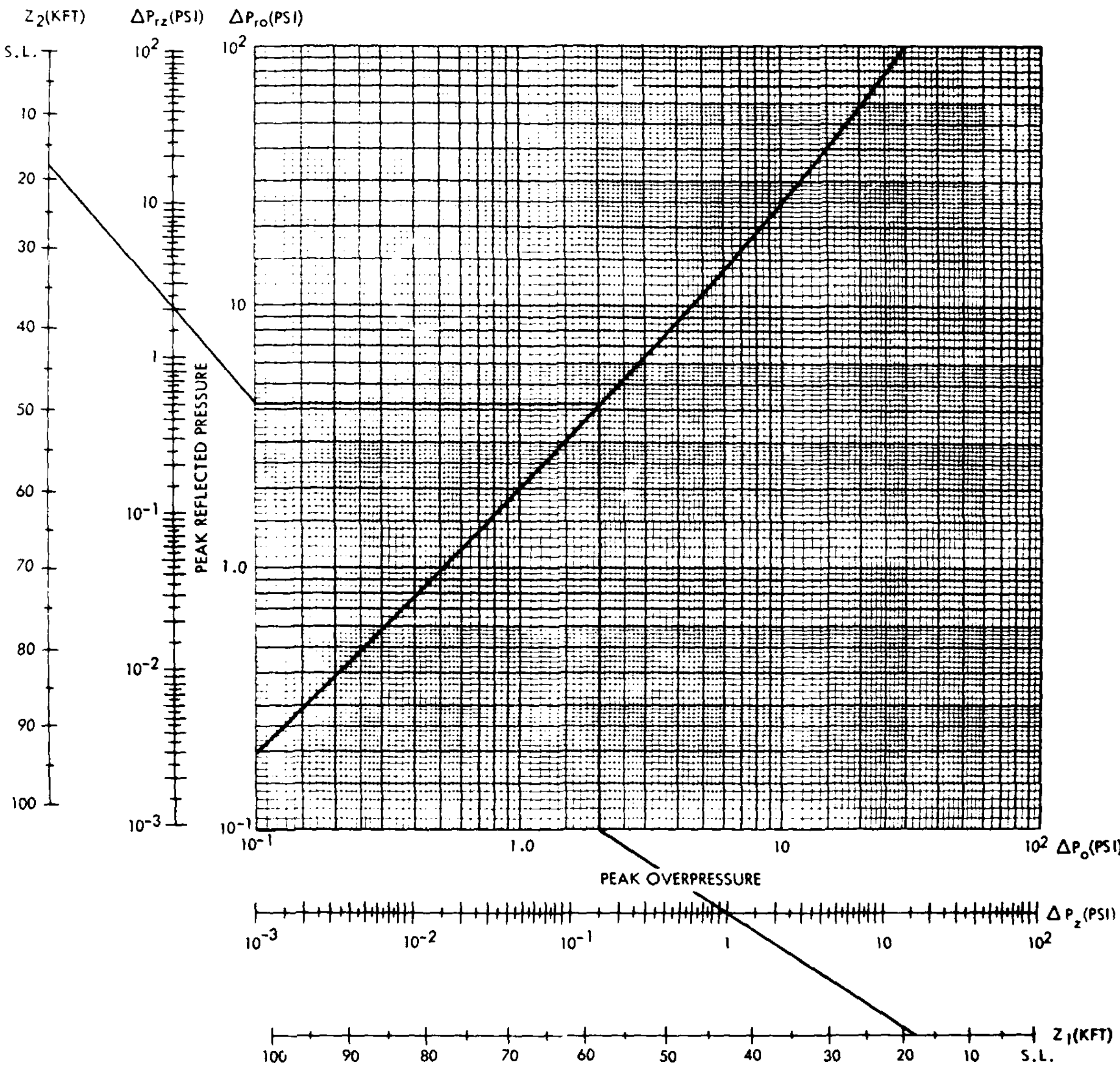


Figure 2-12 Peak Reflected Pressure versus Peak Incident Overpressure (Low Range)

Figure 2-13

Peak Reflected Pressure versus Peak Incident Overpressure (High Range)

The curve in Figure 2-13 gives the peak reflected pressure (instantaneous reflected pressure) as a function of the overpressure for a shock wave striking a surface at normal incidence. The instantaneous value of the peak reflected pressure is calculated from the Rankine-Hugoniot relation:

$$\Delta P_{ro} = 2\Delta P_o \left[(7P_o + 4\Delta P_o)/(7P_o + \Delta P_o)\right]$$

where:

ΔP_{ro} is the peak reflected pressure - psi

ΔP_o is the peak incident overpressure - psi

P_o is the ambient pressure - 14.7 psi

By the use of the nomograms, the peak reflected pressure, ΔP_{rz}, as a function of the peak incident overpressure, ΔP_z, may be found for any burst altitude, Z.

The example shows that for a peak incident overpressure of 350 psi at an altitude of 18,000 ft the peak reflected pressure is 2500 psi.

The procedure is as follows:

Step 1 - Connect 350 on ΔP_z scale with 18 on Z_1 scale and extend the line to ΔP_o scale; read ΔP_o = 700 psi.

Step 2 - At ΔP_o = 700 follow parallel vertical lines (values of constant ΔP_o) to curve; from intersection point on curve follow parallel horizontal lines (values of constant ΔP_{ro}) to ΔP_{ro} scale; read ΔP_{ro} = 5000 psi.

Step 3 - Connect 5000 on ΔP_{ro} scale with 18 on Z_2 scale ($Z_1 = Z_2$); read ΔP_{rz} = 2500 psi on ΔP_{rz} scale.

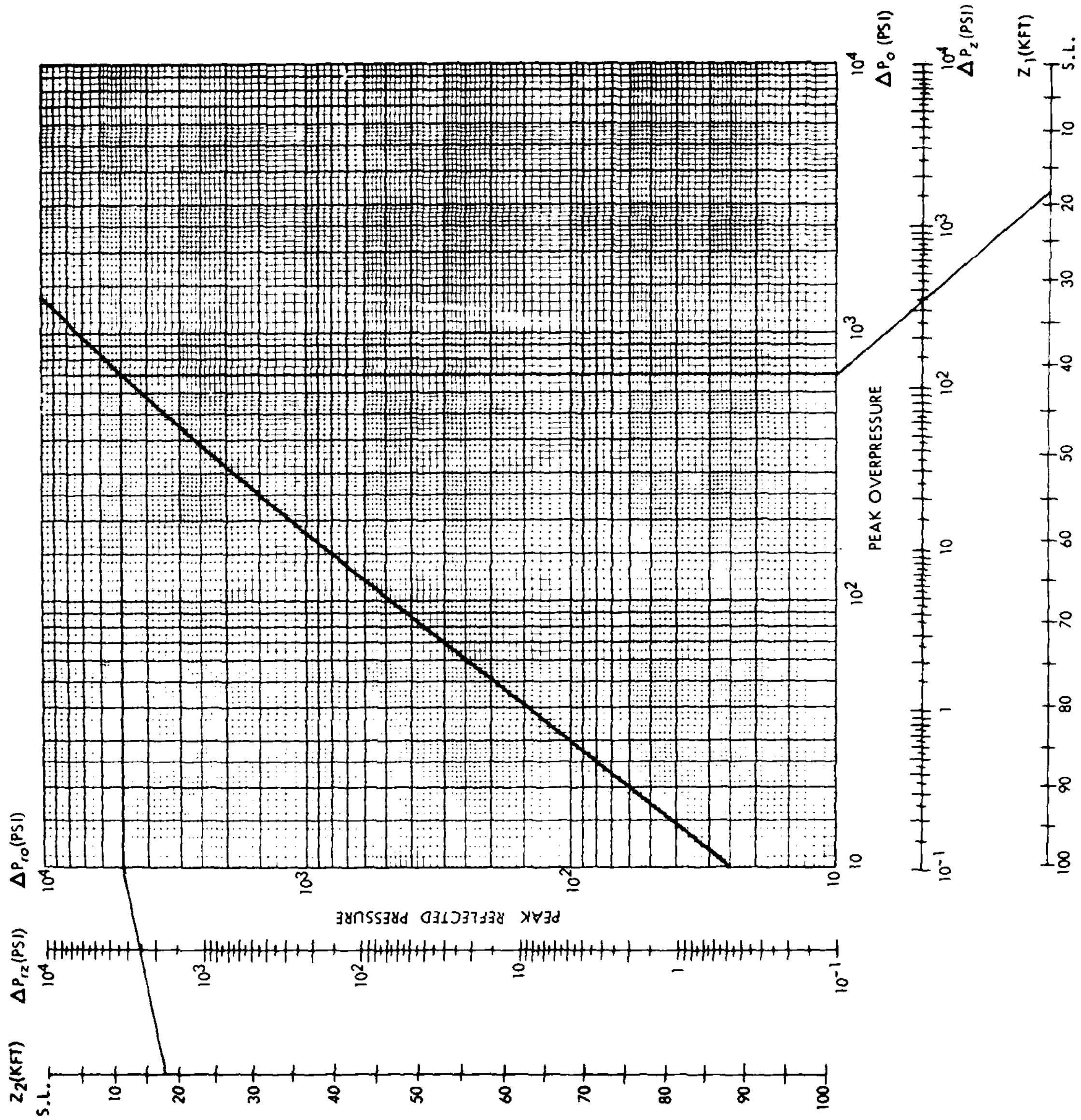


Figure 2-13   Peak Reflected Pressure versus Peak Incident Overpressure (High Range)

Figure 2-14

Height-Of-Burst Curves - Peak Overpressure

These sets of curves give the peak overpressure along the ground surface as a function of the height-of-burst (HOB) and the horizontal range from ground zero for a one-pound TNT charge in a sea level atmosphere (14.7 psi). These curves are based on the data from NOLTR 65-218 and private communication from BRL on the distant plain series for 20-100 tons of TNT.

These curves may be scaled to other yields by the cube root scaling equations:

$$\lambda_{ro} = R_1 \text{ (ft)}/W_1 \text{ (lbs TNT)}^{1/3}$$

$$\lambda_{ho} = H_1 \text{ (ft)}/W_1 \text{ (lbs TNT)}^{1/3}$$

where:

λ_{ro} is the scale horizontal range from ground zero

λ_{ho} is the scaled burst height from ground zero

R_1 is the absolute horizontal range from ground zero

H_1 is the absolute burst height from ground zero

W_1 is the yield of interest.

For explosives other than TNT, determine their TNT equivalence from Table 2-1 or 2-3.

EXAMPLE A:

The example in Figure 2-14 shows that a one-pound TNT burst at a height, λ_{ho}, at 25 ft gives a peak overpressure of 2 psi at a horizontal range, λ_{ro}, of 30 ft from ground zero.

The procedure is as follows:

Step 1 - At a height of burst, λ_{ho} of 25 ft/(lbs TNT)$^{1/3}$ follow parallel horizontal lines (values of constant λ_{ho}) to the 2 psi curve.

Step 2 - From intersection point on curve follow parallel vertical lines (constant values of λ_{ro}) to λ_{ro} scale; read 30 ft/(lbs TNT)$^{1/3}$.

EXAMPLE B:

For an 8.14-lb Pentolite charge fired at altitude of 40 ft, find the horizontal range from ground zero for the 1 psi peak overpressure level.

The procedure is as follows:

Step 1 - From Table 2-3 one pound of Pentolite is equivalent to 1.17 lbs of TNT. Then 8.14 lbs of Pentolite is equivalent to 9.52 lbs of TNT.

Step 2 - $\lambda_{ho} = R_1/(W_1)^{1/3}$

$\lambda_{ho} = 40/(9.52)^{1/3}$

$\lambda_{ho} = 19 \text{ ft/(lbs TNT)}^{1/3}$

Step 3 - At a height of burst, λ_{ho}, of 19 ft/(lbs TNT)$^{1/3}$ follow parallel horizontal lines (values of constant λ_{ho}) to the 1 psi curve.

Step 4 - From intersection point on curve follow parallel vertical lines (constant values of λ_{ro}) to λ_{ro} scale; read 70 ft/(lbs TNT)$^{1/3}$.

Step 5 - $\lambda_{ro} = R_1/(W_1)^{1/3}$

$\lambda R_1 = \left[70 \text{ ft/(lbs TNT)}^{1/3}\right] \times \left[9.52 \text{ (lbs TNT)}^{1/3}\right]$

$R_1 = 148$ ft - Answer.

Subscript o denotes conditions at sea level.

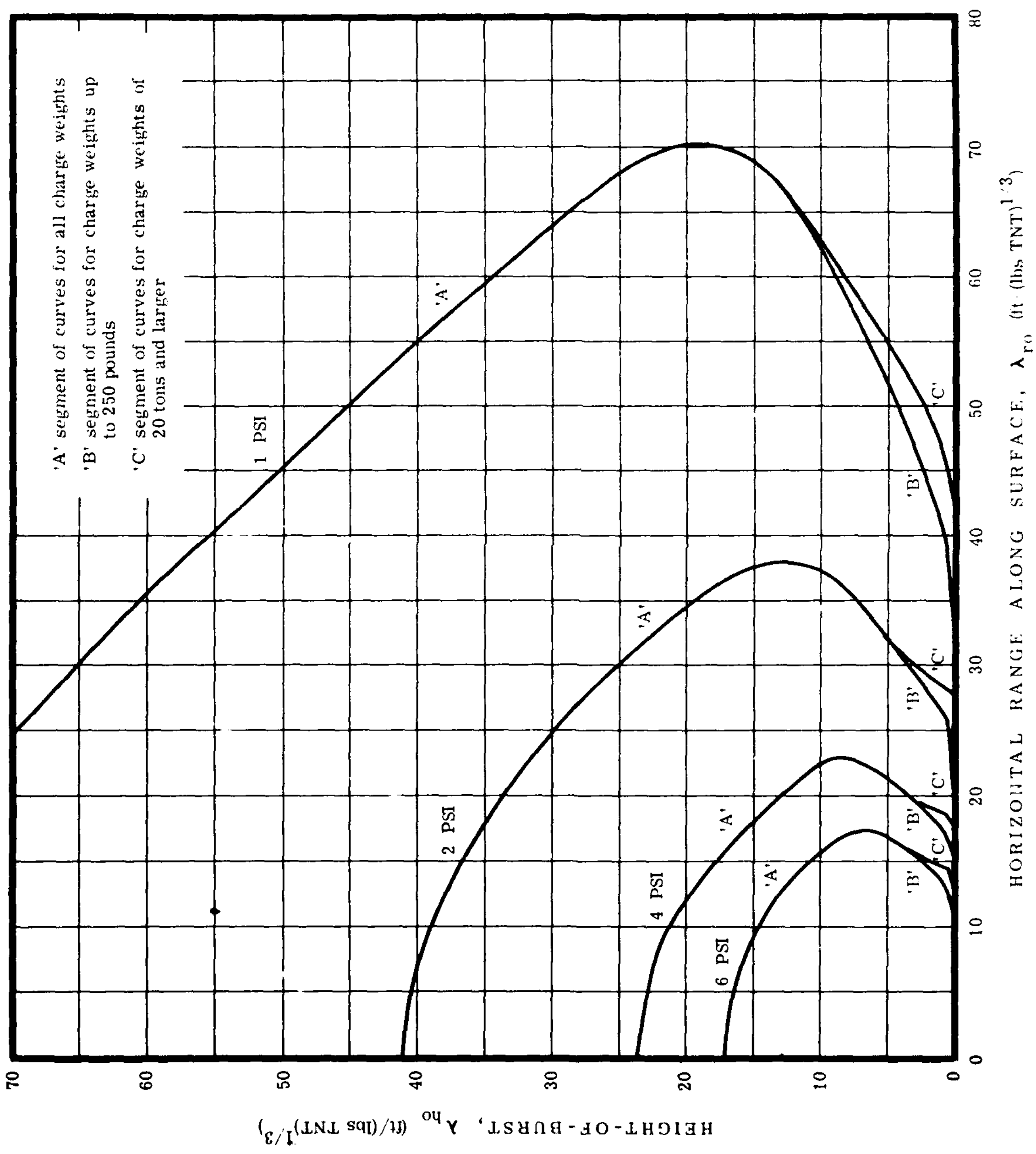


Figure 2-14 Height-of-Burst Curves—Peak Overpressure

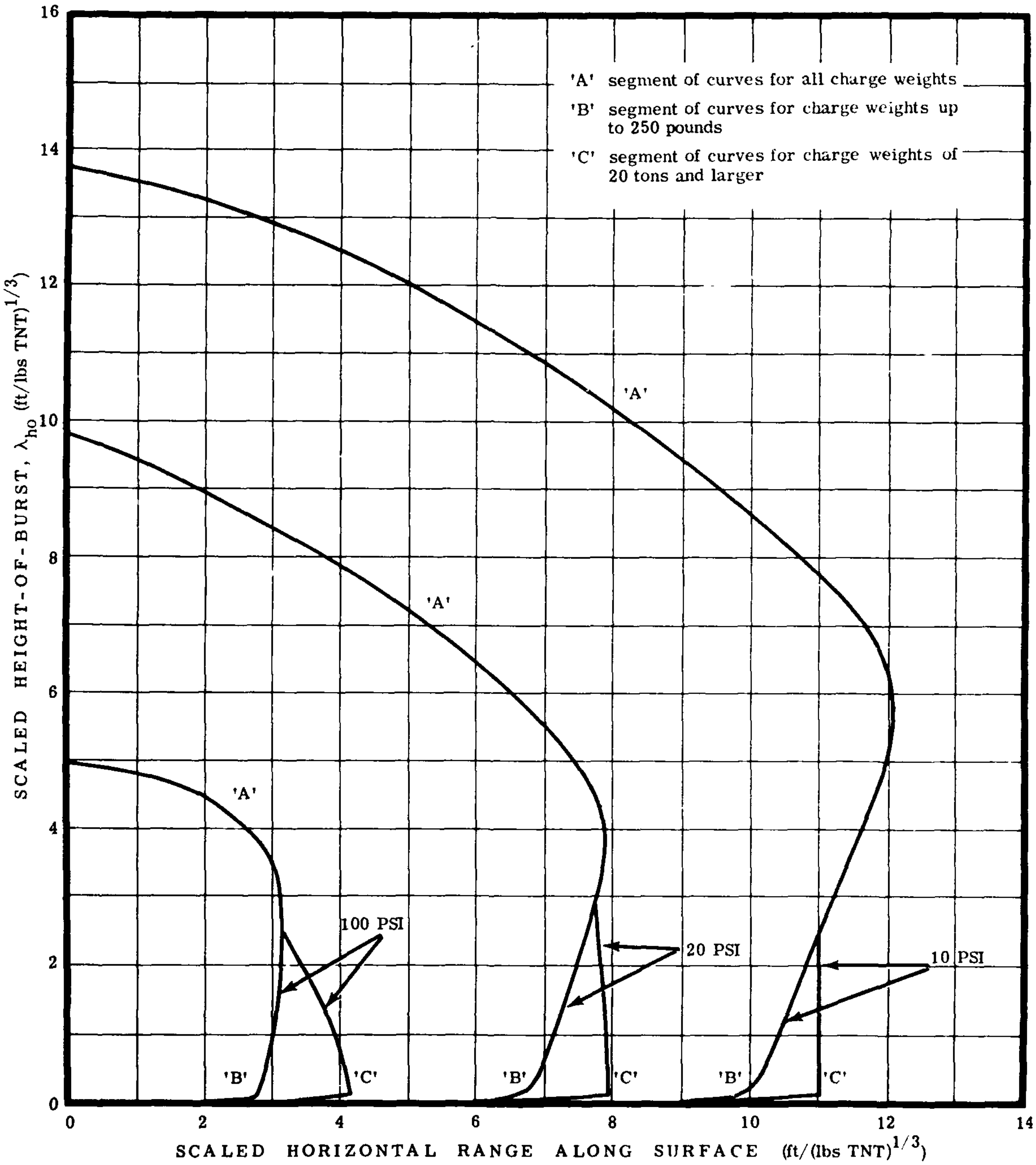


Figure 2-15 Height-of-Burst Curves— Peak Overpressure

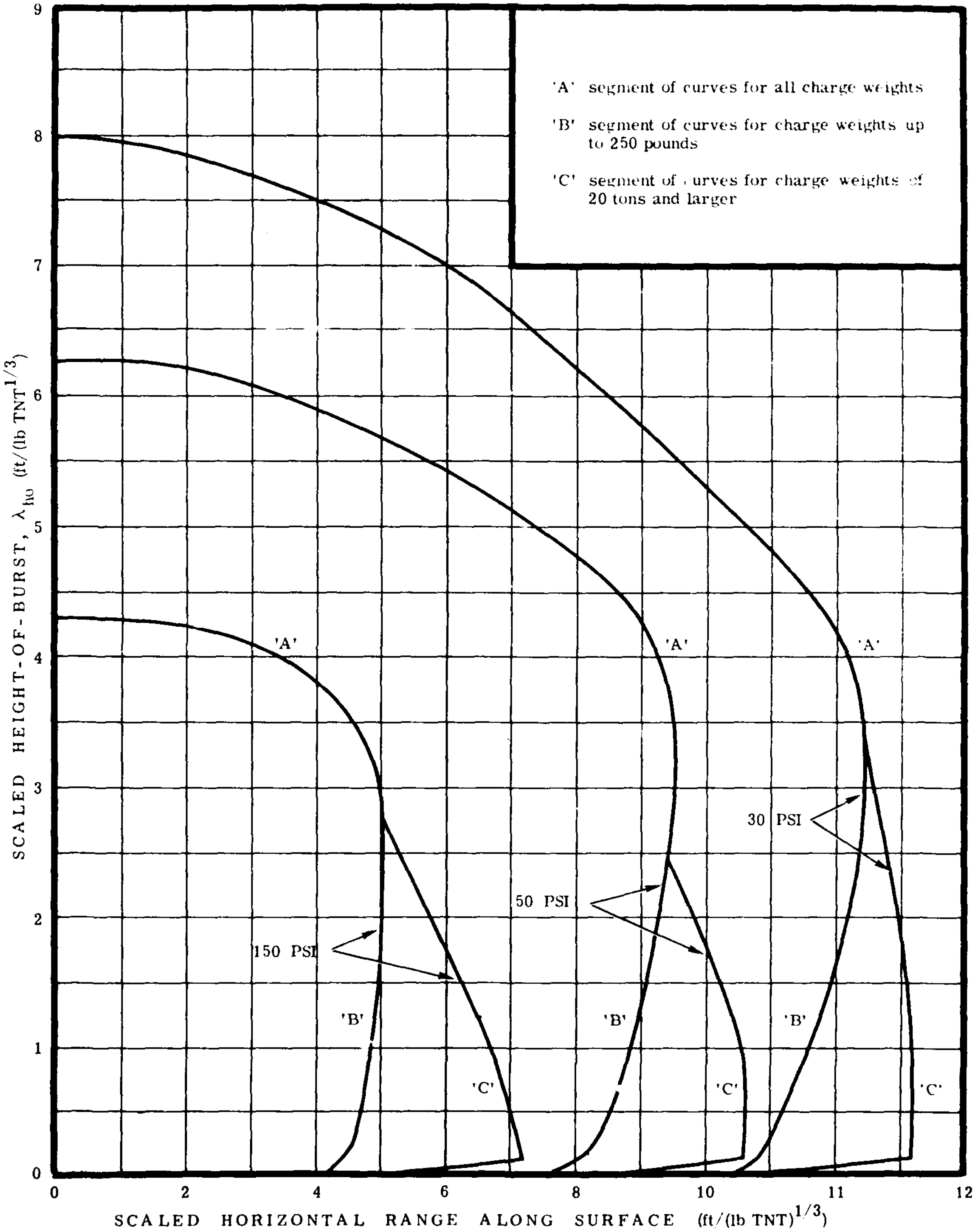


Figure 2-16 Height-of-Burst Curves—Peak Overpressure

Figure 2-17

Positive-Overpressure Impulse at the Surface (TNT)

Figure 2-17 gives positive-overpressure impulse as a function of height-of-burst and ground range for a 1-lb burst in a homogeneous sea-level atmospher and represents the area under the positive phase of the overpressure-time curve at or near the reflecting surface. (Reference 21)

SCALING:

For yields other than 1 lb, scale as follows:

$$I_1/I_2 = h_1/h_2 = d_1/d_2 = (W_1)^{1/3}/(W_2)^{1/3}$$

where I_1, h_1, and d_1 are impulse, height-of-burst and ground distance for yield W_1 and I_2, h_2, and d_2 are the corresponding elements for yield W_2.

EXAMPLE:

Given: A 600,000-lb charge burst at a height of 500 ft.

Find: The overpressure positive-phase impulse on the surface at a ground range of 826 ft.

Solution: The corresponding ground distance and height-of-burst for 1 lb is:

$$h_1 = h_2 (W_1)^{1/3}/(W_2)^{1/3} = 500 \times 1/84.4 = 5.93 \text{ ft}$$

$$d_1 = d_2 (W_1)^{1/3}/(W_2)^{1/3} = 826 \times 1/84.4 = 9.8 \text{ ft}$$

From Figure 2-17 for a height-of-burst of 5.93 ft at a ground range of 9.8 ft, the impulse is about 10 psi-msec.

Answer: Therefore, for 600,000 lbs at a height-of-burst of 500 ft, the overpressure impulse at a ground range of 826 ft will be:

$$I_2 = I_1 (W_2)^{1/3}/(W_1)^{1/3} = 10 \times 84.4$$
$$= 844 \text{ psi-msec}$$
$$= 0.84 \text{ psi-sec}$$

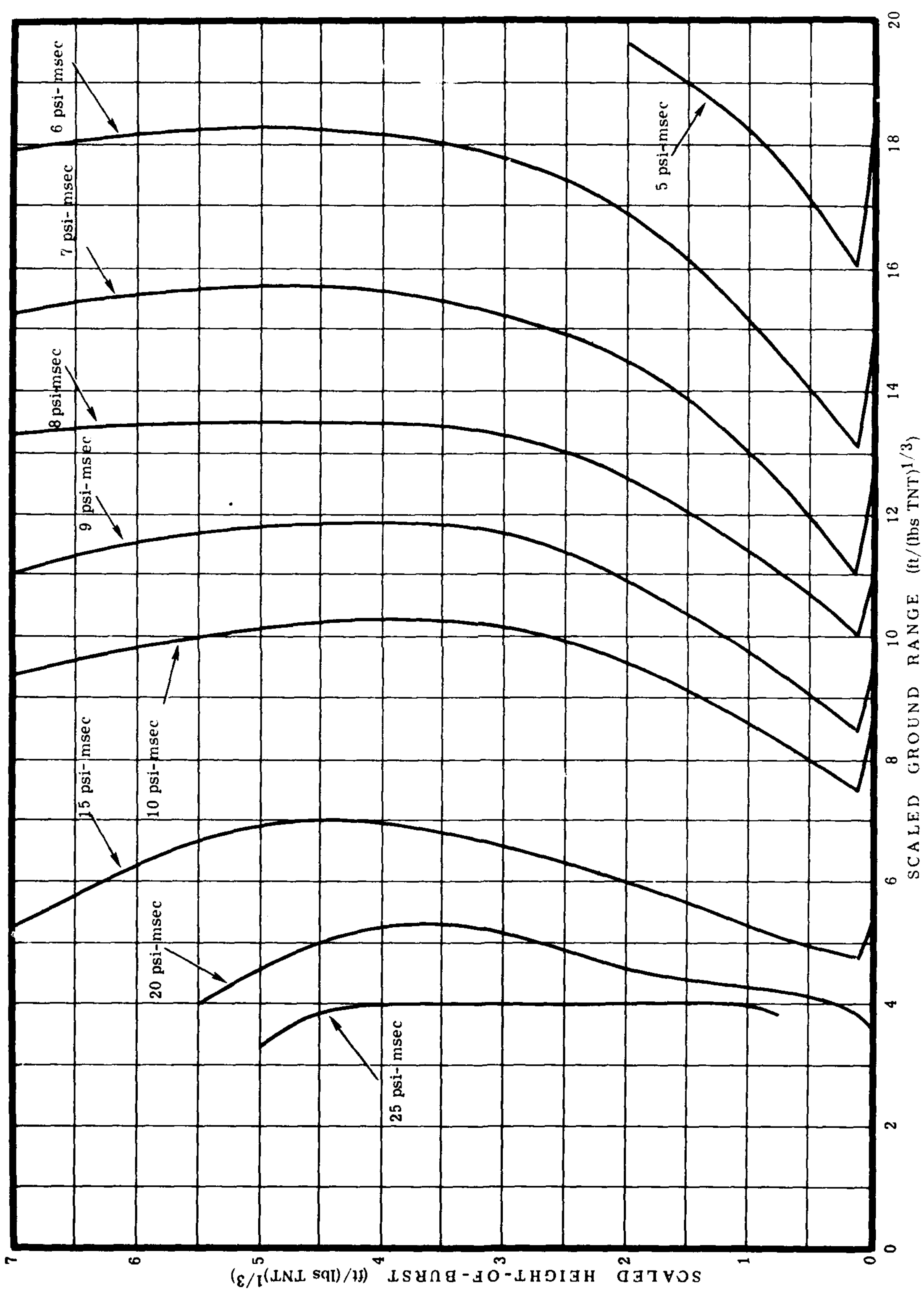


Figure 2-17 Positive Overpressure Impulse at the Surface (HOB)

Figure 2-18

Positive-Overpressure Duration on the Surface (TNT)

Figure 2-18 gives positive-overpressure durations on the ground as a function of ground range and burst height for a 1-kt burst under sea-level conditions.

SCALING:

For yields other than 1 kt, scale as follows:

$$h_1/h_2 = d_1/d_2 = (W_1)^{1/3}/(W_2)^{1/3} = t_1/t_2$$

where h_1, d_1, and t_1, are the height-of-burst, range, and duration for yields W_1, and h_2, d_2, and t_2 are the corresponding quantities for yield W_2.

EXAMPLE:

Given: An 8,000 lb explosion at a height-of-burst of 100 ft.

Find: The positive overpressure duration at a ground range of 200 ft.

Solution: The corresponding 1-lb height-of-burst is $h_1 = 100/20 = 5$ ft and the corresponding ground range is $d_1 = 200/20 = 10$ ft.

Figure 2-19

Distance for TNT Surface Burst

The use of the curve is illustrated as follows: At a distance of 44 ft from a surface burst (half buried) of 100 lbs of pentolite, the peak overpressure is 8.5 psi. (Reference 3)

The procedure is as follows:

Step 1 - From Table 2-3, 100 lb of pentolite is equivalent to 116 lbs of TNT (100 x 1.16).

Step 2 - The cube root of 116 = 4.88 (lbs TNT)$^{1/3}$, and thus $\lambda_o = 44$ ft/4.88 (lbs TNT)$^{1/3}$ = 9.03 ft/(lbs TNT)$^{1/3}$.

Step 3 - Using Figure 2-19 at $\lambda_o = 9.03$ follow parallel vertical lines (values of constant λ_o) to curve. From intersection point on curve follow parallel horizontal lines (values of constant ΔP_o) to P_o scale: read $\Delta P_o = 8.5$ psi.

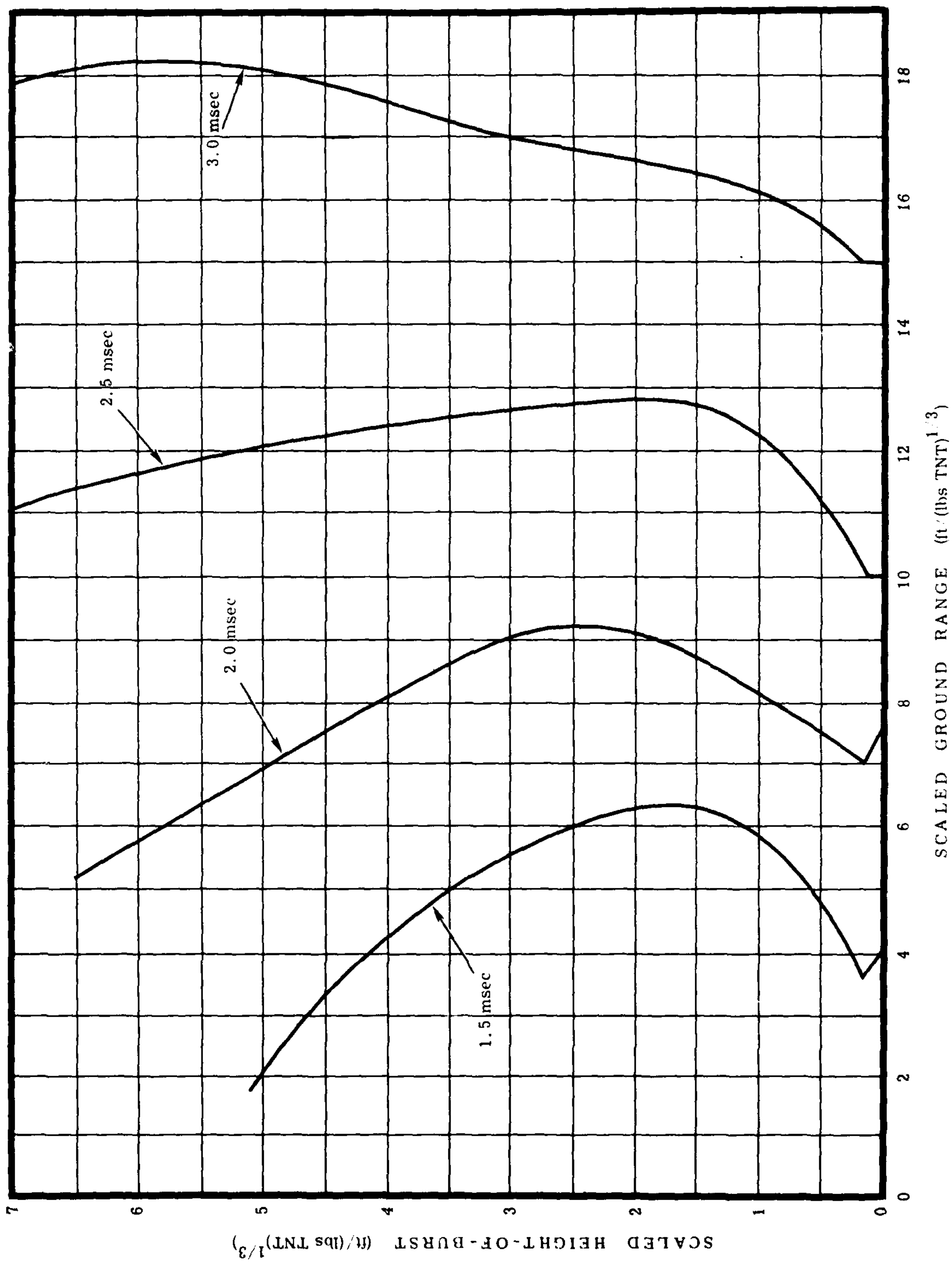


Figure 2-18 Positive Overpressure Duration on the Surface (TNT)

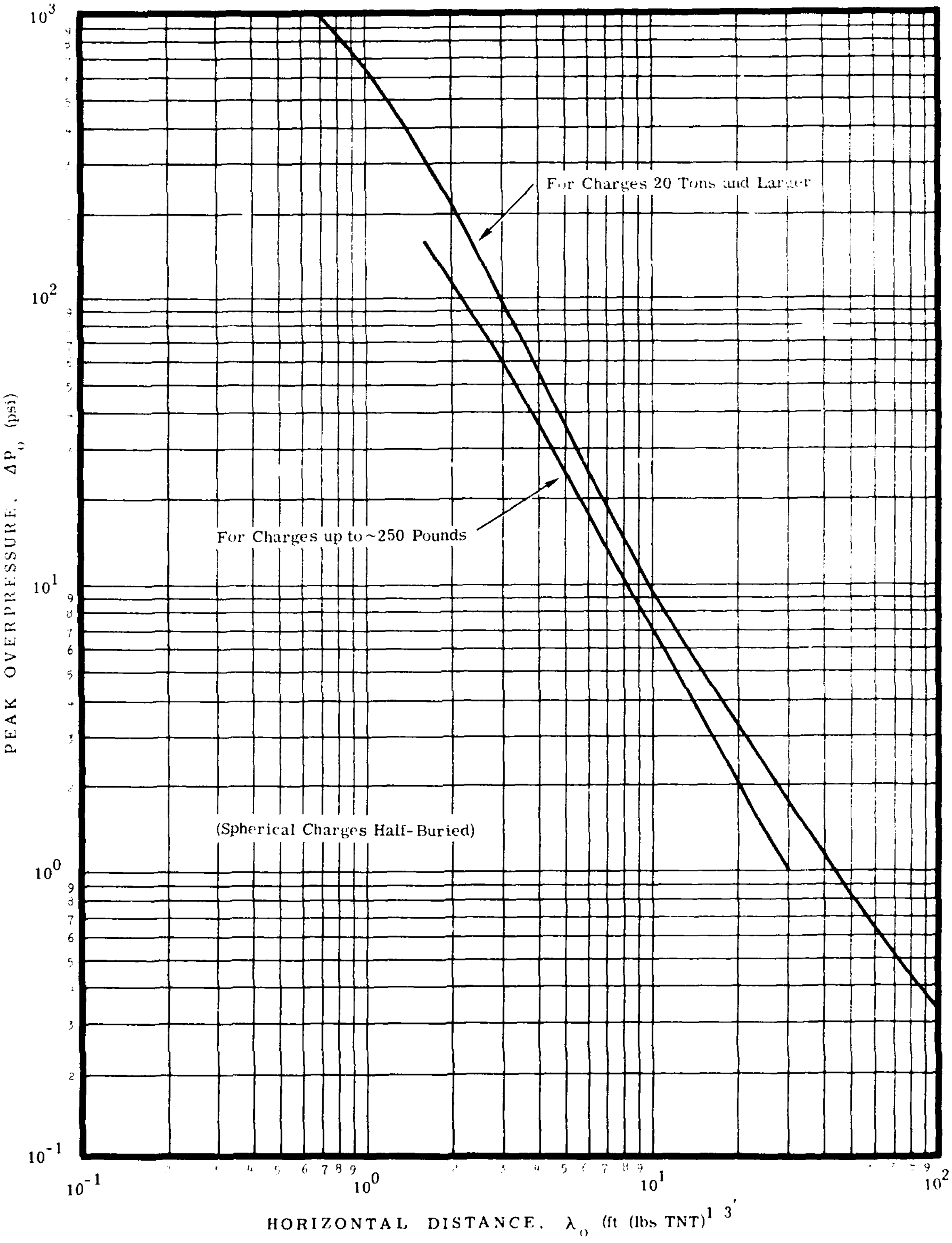
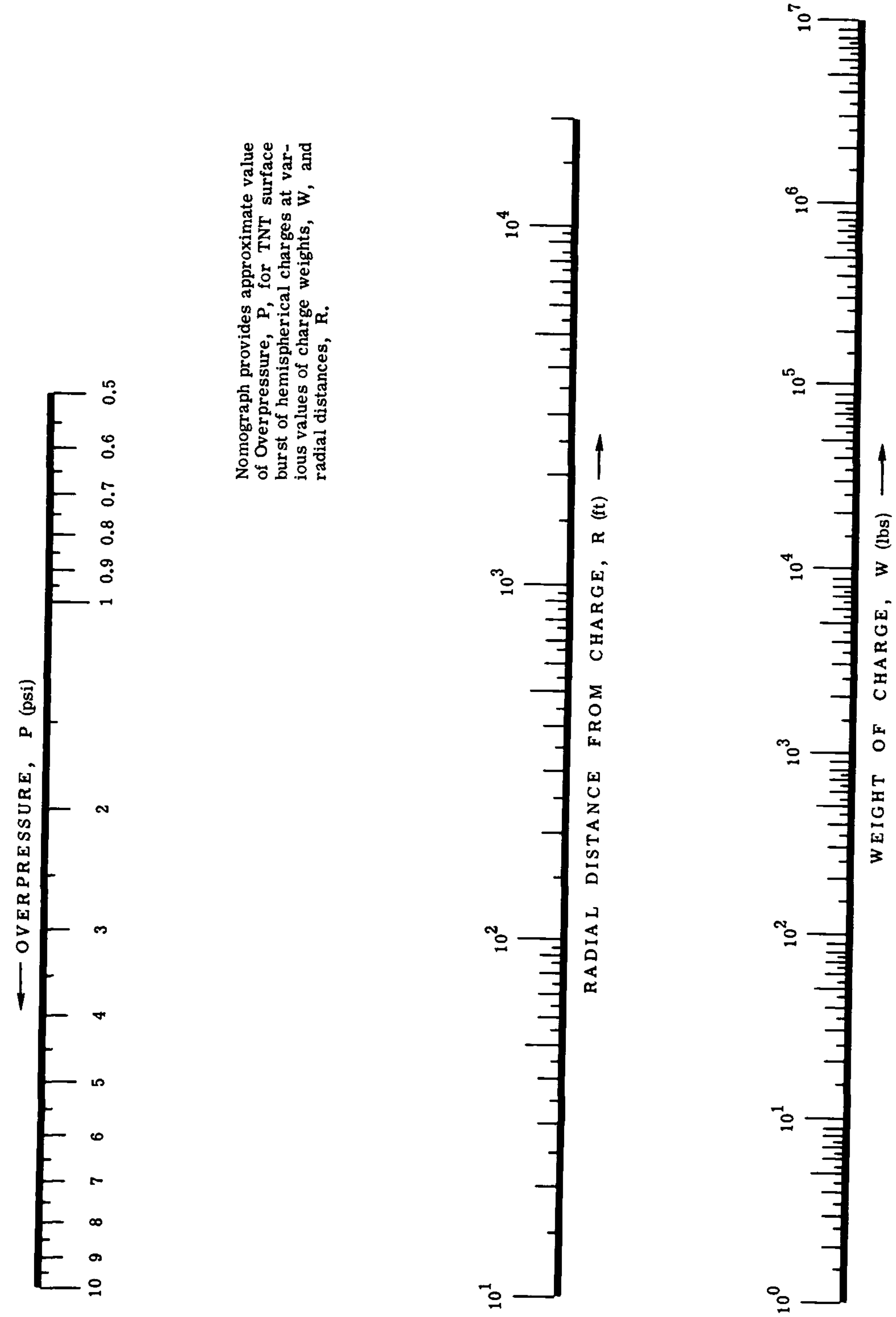


Figure 2-19 Peak Overpressure versus Distance Surface Burst (Reference 21)



Nomograph provides approximate value of Overpressure, P, for TNT surface burst of hemispherical charges at various values of charge weights, W, and radial distances, R.

Figure 2-20 Overpressure versus Distance versus Charge Weight

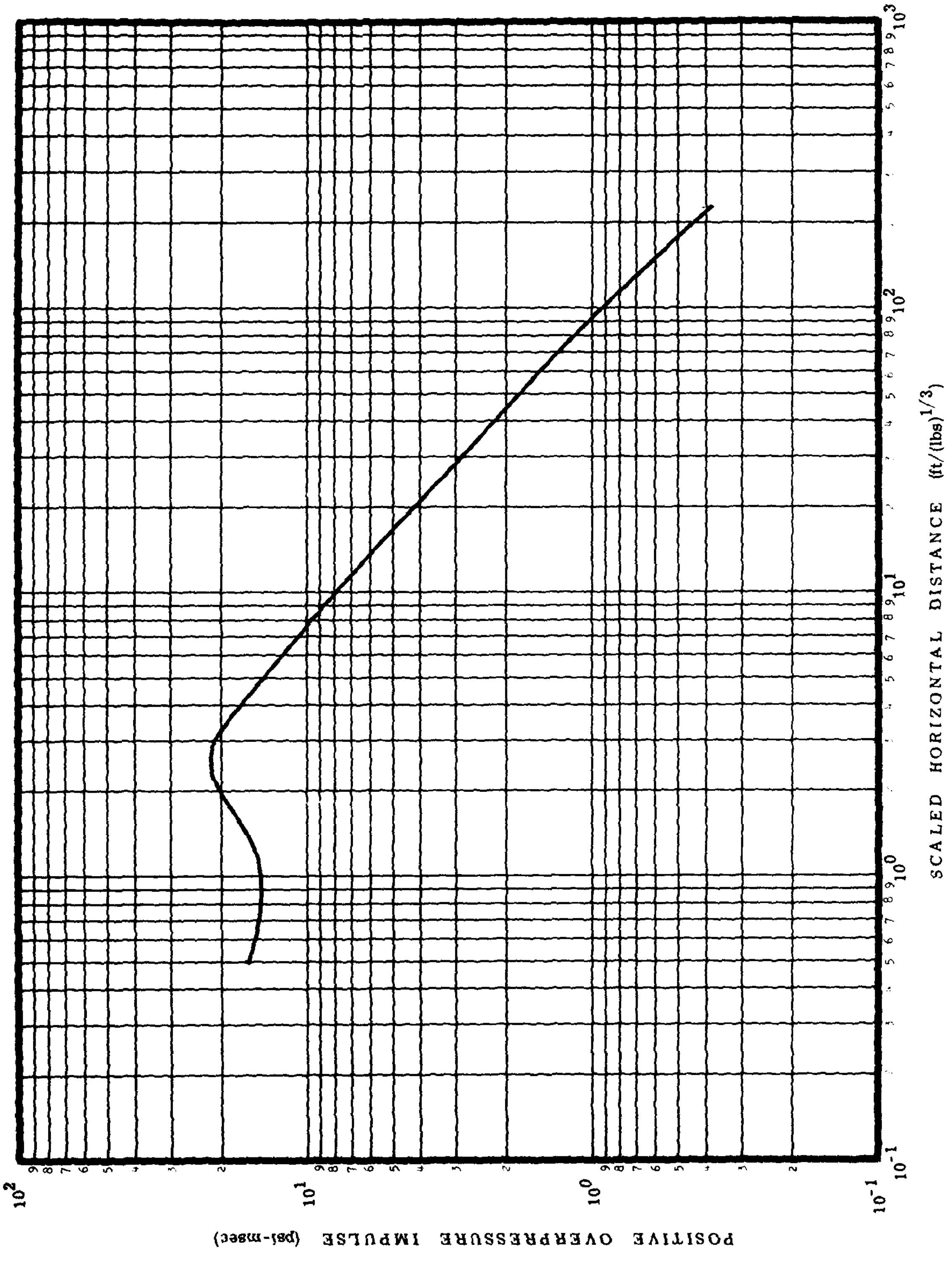


Figure 2-21 Positive Overpressure Impulse for Spherical TNT Charge Surface Burst (Reference 6)

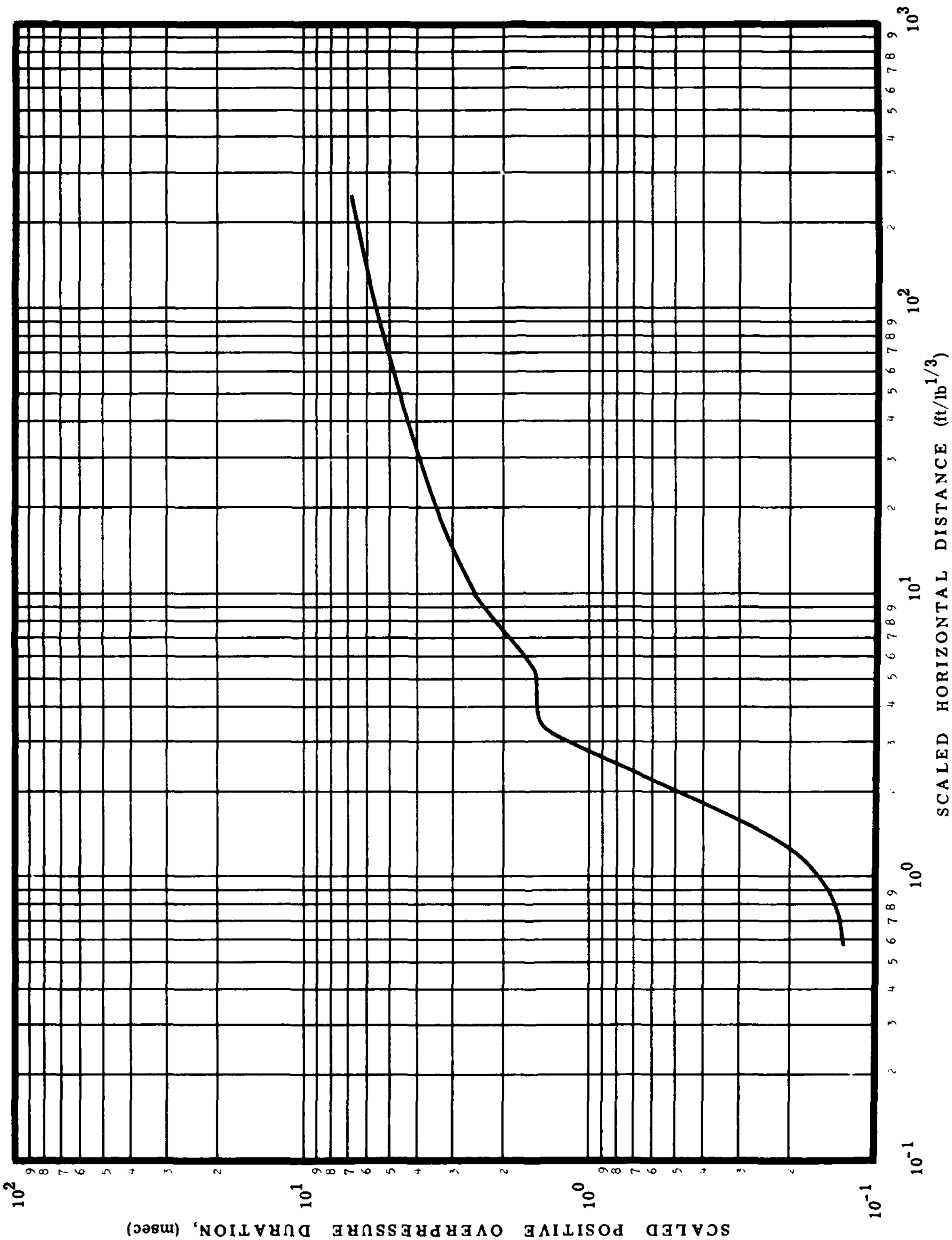


Figure 2-22 Positive Duration for Spherical TNT Charge Surface Burst (Reference 6)

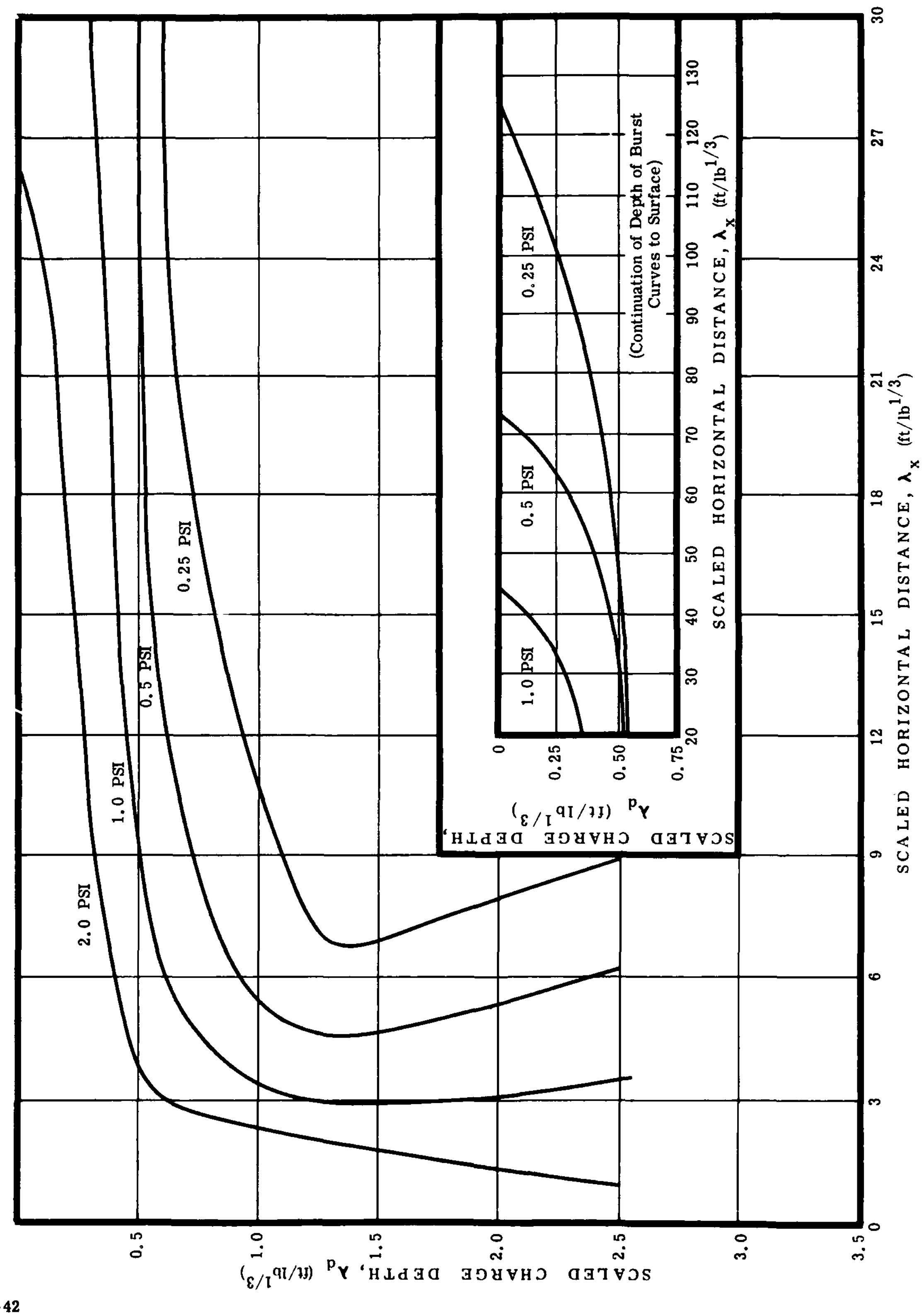


Figure 2-23 Constant Air Blast Pressures along a Line Parallel to the Water Surface from TNT Spheres Fired Underwater, λ_y Fixed at 0.25

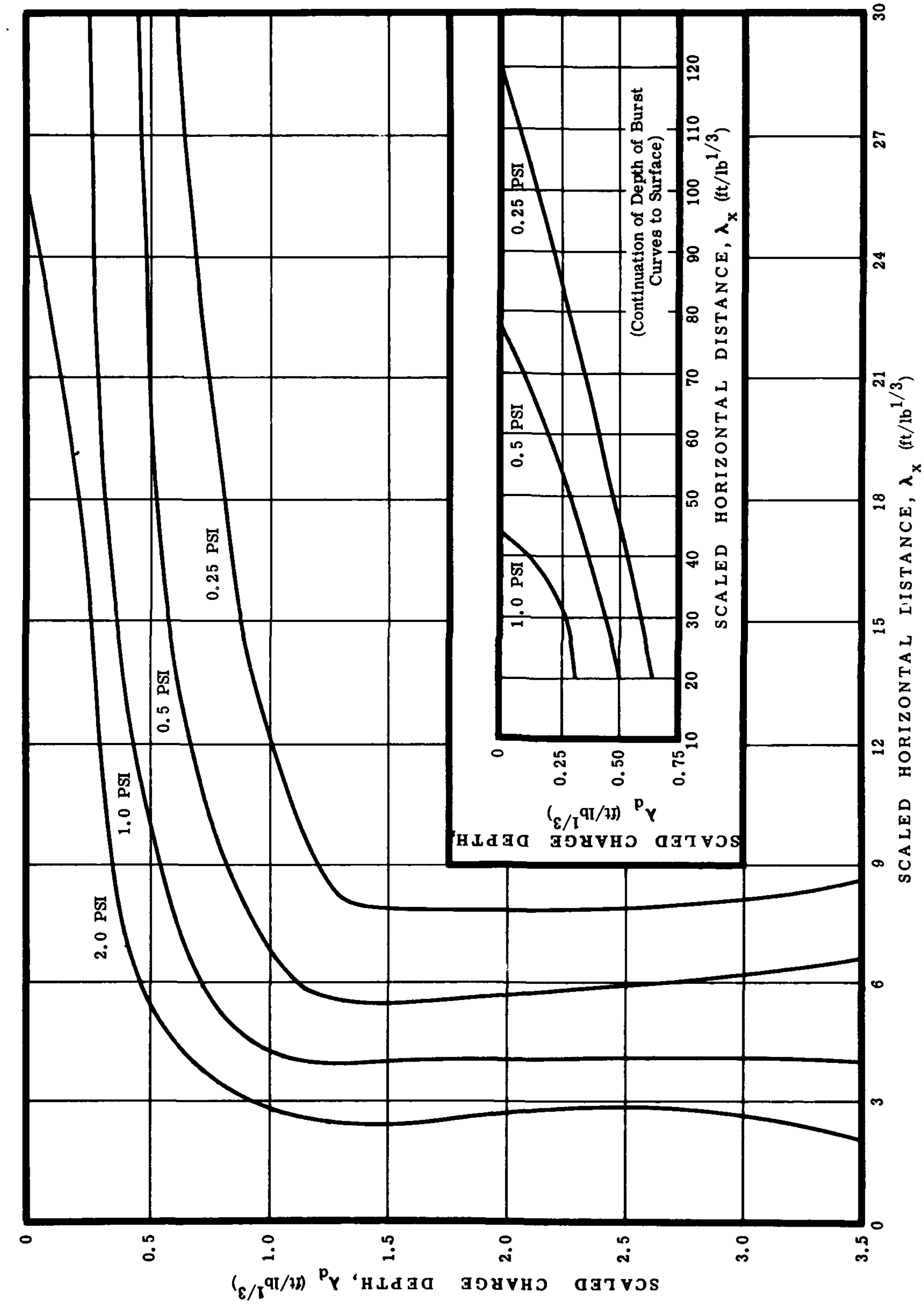


Figure 2-24 Constant Air Blast Pressures along a Line Parallel to the Water Surface from TNT Spheres Fired Underwater, λ_y Fixed at 3.0

Figure 2-25

Predictions of Airblast from Underground Bursts

The curve in Figure 2-25 gives the peak overpressure from underground bursts as a function of $\bar{x}$, adjusted ground range. The adjusted ground range is a function of the ground range, yield, specific gravity of the soil, and the depth of burst. The curve for peak overpressure is based on the theoretical blast wave curves of Kirkwood and Brinkley (NDRC Report No. A-341). The prediction method comes from Reference 8.

The use of the curve is illustrated as follows: The peak airblast overpressure that can be expected at a ground range of 50 ft if 1000 lbs of TNT are exploded 5 ft below the surface of alluvium is 6 psi.

The procedure is as follows:

Step 1 - $\lambda_d = D/W^{1/3} = 5 \text{ ft}/(1000 \text{ lbs})^{1/3}$

$\lambda_d = 0.5 \text{ ft/lbs}^{1/3}$

Step 2 - From Table 2-4, $\rho = 1.6$

$\rho\lambda_d = (1.6)\ (0.5) = 0.8 \text{ ft/lbs}^{1/3}$

Step 3 - $e^{\rho\lambda_d} = e^{0.8} = 2.22$

Step 4 - $\lambda_{\bar{x}} = \bar{x}/W^{1/3} = 50/(1000)^{1/3} = 5$

Step 5 - $\bar{x} = \lambda_{\bar{x}} e^{\rho\lambda_d} = (5)\ (2.22) = 11.1$

Step 6 - From Figure 2-25 read 6 psi.

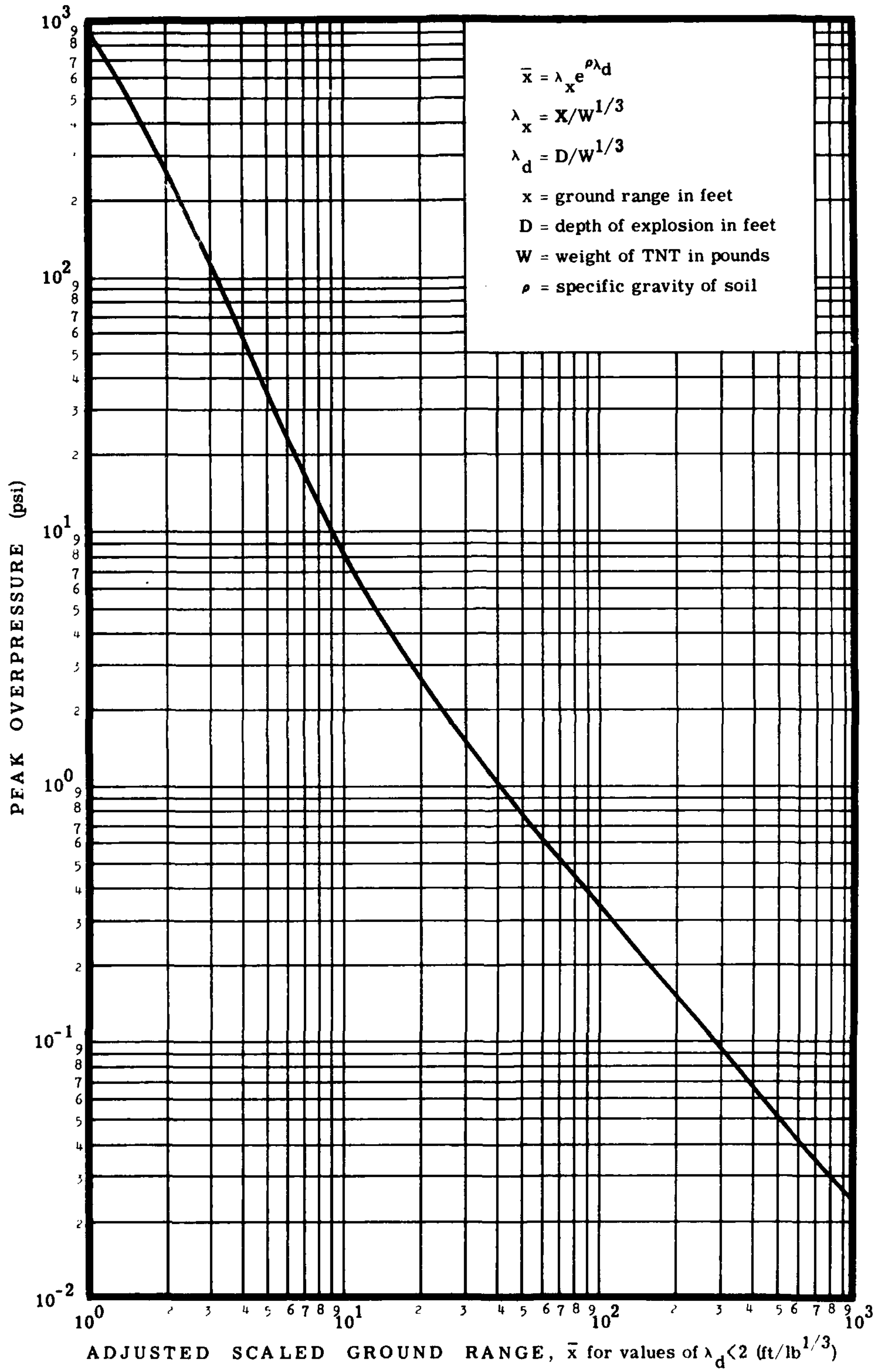


Figure 2-25 Peak Overpressure from Underground Bursts

Figure 2-26

Static Pressure vs Volume of Enclosed Space and Weight of Charge

Figure 2-26 gives the static pressure for a given chamber volume and charge weight for a heat of combustion, h, of 1 kcal/gm. At the higher charge weight to chamber volume ratios, the plot is believed to be conservative, i.e., the static pressures predicted are too high. This results because, on one hand, the mean gamma (γ) of the gas drops with increased temperature and increased proportion of explosion product gases; and, on the other hand, there is an increment of pressure due to the added number of molecules of explosion product gases. These factors are not accounted for here. The use of Figure 2-26 and Table 2-5 is illustrated in the example. (Reference 10)

Example:

Find the static pressure which will be generated by 10 lb of PETN in an enclosed space of volume 2,000 ft^3.

Solution:

Step 1 - Find 2,000 on the volume scale and move vertically to the diagonal for 10 lb.

Step 2 - From that point, move horizontally to the static pressure scale and read 20 psi.

Step 3 - Multiply the static pressure obtained from the plot by the heat-of-combustion factor for PETN, 20.0 psi/kcal x 1.95 kcal = 39.0 psi.

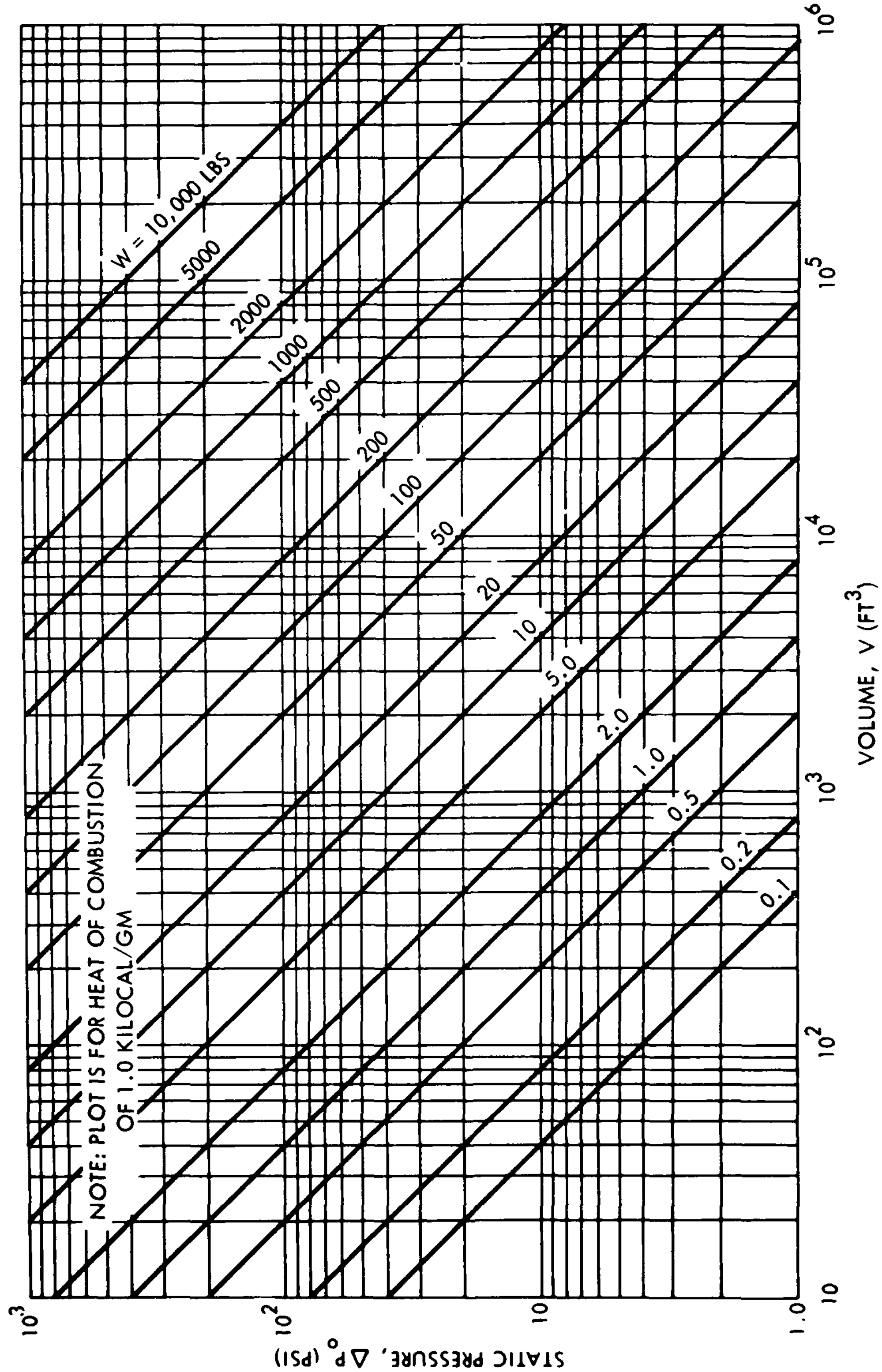


Figure 2-26 Static Pressure versus Volume of Enclosed Space and Weight of Charge

2-5 FRAGMENTATION

The gross material thrown out by explosions can be significant cause of damage. The case surrounding the explosive, the barricade wall or structure in which the explosion occurs, and the very ground on or over which the explosion takes place, all can contribute to throwout of fragmented material. These fragments, traveling at high velocities, can cause detonations of nearby explosives and direct structural damage to surrounding structures.

Some of the parameters important to case fragmentation are presented here: initial fragment velocity and striking velocity and depth of penetration as functions of case fragment size are given. The maximum distance attained by fragments for a wide range of explosions (other than controlled cased charge tests) also is presented; the fragments are not identified as to source or size.

2-5.1 FRAGMENT VELOCITIES FROM SMALL CHARGE DETONATIONS (Reference 3).

a. The initial velocity of a fragment can be found for cylindrical metal cases by the Gurney Law (Figure 2-27 and Table 2-7).

b. The striking velocity of a fragment that strikes a target a distance away from an exploding missile can be found in Figure 2-28.

c. The depth of penetration of mild steel versus striking velocity can be found in Figure 2-29. Estimates of fragment penetration in materials other than mild steel can be obtained from Table 2-6 of equivalents. (Reference 22).

d. The maximum horizontal range for fragment travel versus initial velocity and departure angle can be found in Figures 2-30 and 2-31.

Table 2-6

Mild Steel Equivalents for Estimating Fragment Penetration in Various Materials

1" pine wood	$\simeq$ 1/20" mild steel
1" armor plate	$\simeq$ 1-1/4" mild steel
1" dural plate	$\simeq$ 1/3" mild steel
10" reinforced concrete slab	$\simeq$ 1" mild steel
12" brickwork	$\simeq$ 1" mild steel
30" sand	$\simeq$ 1" mild steel

2-5.2 FRAGMENT RANGE AND DISTRIBUTION RELATIONSHIPS FOR EXPLOSION INCIDENTS.

Figure 2-32 provides a broad-band curve covering many of the available fragment data points for incidents and tests with high explosives which shows the relationship between explosive weight and maximum fragment distance. Figures 2-33, 2-34 and 2-35 show the relationship between fragment distribution by weight and number as a function of range for the same selected incidents with fullscale and launch vehicles and/or tests. The detailed supporting data from the tests which were studied is given in Tables 2-8 and 2-9.

2-5.3 SPACE VEHICLE FRAGMENTATION HAZARDS.

The propagation of fragments from an exploding space vehicle differs from that of standard munitions for a number of reasons. It is not possible to postulate any well-founded criteria on the basis of the limited data presented in the foregoing sections but by inserting the data points from the launch vehicle incidents in the high explosive experimental data (Figure 2-32), it can be seen in Figure 2-36 that the boundary limits of the envelope are respected by space vehicle fragments. This lends some credence to the position that the upper limit of Figure 2-32 may be considered applicable to high order explosive reactions of propellants while the lower boundary is certainly a result to be expected in the case of widely distributed and low order reactions (deflagration ⟶ low order explosion).

2-5.3.1 Vehicle Failure Modes. Space vehicles/missiles contain essentially low energy/density, or distributed explosives, which should be properly contrasted with the high energy/density, or concentrated explosives (HE) from which the standard fragmentation data are derived. Generally we may expect that exploding space vehicles will generate a high ratio of non-ballistic (sheet) fragments which cannot be expected to travel as predictably (or as far) as ballistic fragments from a compact HE container. Comparisons have been made on the basis of TNT equivalence, which is also estimated, and the application of this warhead and munitions data have led to the establishment of conservative distance or danger ratios.

During the course of conducting Project PYRO several failure modes were investigated to examine the cases of confinement by the missile tankage (CBM), and confinement by the ground surface (CBGS) while examining various conditions of ignition time, size of tank rupture opening, length to diameter ratio of tankage, ullage volume, tank wall thickness (burst pressure), ignition time and the relative shapes, velocities and orientation of propellant masses involved. Characteristically, the tests demonstrated an unpredictable ignition time, low peak overpressures at close-in distances (relative to HE data) but for a longer time such that total impulse is higher than that from HE, and a yield that tended to flatten out at larger and larger quantities of propellant. This will result in a modification of the blast damage experienced by targets as compared with tests where HE was the reference material. The fact that yield per unit weight tended to flatten out with increased total quantity of propellants is supported by experimental evidence obtained by Farber at the University of Florida, Gainesville. Farber showed that as a quantity of cryogenic bi-propellants (in excess of some few thousand pounds) was spilled, sufficient energy from some source caused spontaneous ignition of the system (reference 23). This effect proved to be particularly troublesome in the cryogenic tests of Project PYRO because the experimentally established ignition time was variable and the mixing parameters could not be firmly established for any known time or over any reproducible time interval.

Table 2-7

Table of Gurney's Energy Constant, $(2E)^{1/2}$ for Various Explosive Compositions

Explosives	Composition (Parts by Weight)	Loading Density (g/cm^3)	$(2E)^{1/2}$ (ft/sec)
	Various Cast Explosive Compositions		
Comp B*	RDX/TNT/Wax, 59.4/39.6/1.0	1.68	7880
Comp B*	RDX/TNT/Wax, 57/38/5	1.62	7610
Cyclotol**	RDX/TNT, 25/75	1.67	6920
Cyclotol**	RDX/TNT, 40/60	1.69	7430
Cyclotol**	RDX/TNT, 50/50	1.71	7640
Cyclotol**	RDX/TNT, 70/30	1.72	8380
Cyclotol**	RDX/TNT, 75/25	1.69	7850
	RDX/Wax, 70/30	1.44	6540
	RDX/Wax, 75/25	1.46	7150
	RDX/Al/Wax, 50/15/35	1.44	5980
	RDX/Al/Wax, 52/18/30	1.49	6230
	HMX/Laminac, 60/40	1.46	6230
	HMX/Laminac, 70/30	1.53	6440
HBX-1	RDX/TNT/Al/Wax, 40/38/17/5	1.70	7260
HBX-3	RDX/TNT/Al/Wax, 31/29/35/5	1.81	6510
H-6	RDX/TNT/Al/Wax, 47/31/22/5	1.71	7710
Minol II	Ammonium Nitrate/TNT/Al, 40/40/20	1.68	5870
Pentolite	Pentaerythritoltetranitrate/TNT, 50/50	1.64	7550
Picratol	Explosive D/TNT, 52/48	1.61	6940
PTX-1	RDX/Tetryl/TNT, 30/50/20	1.64	7640
PTX-2	RDX/PETN/TNT, 44/28/28	1.67	7930
TNT**	Trinitrotoluene	1.61	6880
Torpex*	RDX/TNT/Al, 45/37/18	1.79	7450
Tritonal**	TNT/Al, 80/20	1.74	6280
Tritonal*	TNT/Al, 60/40	1.92	5200
	Various Pressed Explosive Compositions		
BTNEN/Wax	bis(Trinitroethyl)Nitramine/Wax, 90/10	1.66	8140
BTNEU/Wax	bis(Trinitroethyl)Urea/Wax, 90/10	1.58	7800
Comp A-3	RDX/Wax, 91/9	1.61	7880
Comp A-J*	RDX/Wax, 95/5	1.64	7950
Comp A-3*	RDX/Wax, 85/15	1.55	7240
Comp B*	RDX/TNT/Wax, 59.4/39.6/1.0	1.59	7660
Comp C*	RDX/TNT/Mononitrotoluene/Dinitrotoluene/Tetryl/ Nitrocellulose, 77/4/5/10/3/1	1.52	7140
Cyclotol*	RDX/TNT, 75/25	1.64	7750
DATB	1,3-Diamino-2,4,6-Trinitrobenzene, 100	1.68	6480
Explosive D	Ammonium Picrate, 100	1.50	6370
Nitroguanidine	Nitroguanidine, 100	1.44	6220
Pentolite*	Pentaerythritoltetranitrate/TNT, 50/50	1.57	7600
RDX*	Cyclotrimethylenetrinitramine, 100	1.59	8040
RDX*	RDX/Al, 80/20	1.71	8270
RDX*	RDX/Al, 60/40	1.82	7260
Tetryl	N-Methylpicrylnitramine, 100	1.63	7460
TNETB*	Trinitroethyltrinitrobutyrate, 100	1.70	8250
TNT	Trinitrotoluene, 100	1.54	6900

*Unpublished Data.

**Unpublished Data, Initial Velocity, for determining $(2E)^{1/2}$ Calculated from Film Analysis and Air Retardation Factor only. The Mean Mass and Presented Area Factor were ignored.

References: 3, 15, and 24 and also NAVORD Reports 2933, 2766, and 4210.

Figure 2-27

Gurney Law for Initial Fragment Velocity

The initial velocity of a fragment can be estimated using the Gurney Equation which assumes that the charge consists of an evenly distributed explosive in a metal case:

$$\text{Cylindrical } V_o = (2E)^{1/2} \left((C/M)/ (1 + C/2M)^{1/2}\right)$$
$$\text{Spherical } V_o = (2E)^{1/2} \left((C/M)/ (1 + 3C/5M)^{1/2}\right)$$

where:

V_o = Initial fragment velocity (ft/sec)

$(2E)^{1/2}$ = Gurney's Explosive Energy Constant (ft/sec)

C = Explosive Weight (Grams)

M = Case Weight (Grams)

For charge configurations which cannot be approximated by the simple cylinder, empirical equations are given in BRL Report 648 (Reference 24).

With a known $(2E)^{1/2}$, C, and M, V_o can be obtained from the nomogram below. Values of $(2E)^{1/2}$ obtained experimentally using 5 inch long steel (SAE 1045) cylinders with 2 inch ID's and 1/4 inch walls, are given in the Table 2-6 for a number of explosives. The value of $(2E)^{1/2}$ varies almost linearly with the density of the explosive; for instance, a variation of 10% in the density will produce a 3 to 8% change in the energy constant. The constant is specific for each explosive and refers to unit mass of explosive. The Gurney constant has been calculated for the experimental loading densities given in Table 2-6. The following example illustrates the use of the nomogram.

Example:

Find the initial fragment velocity of a steel-encased cylindrical charge of Comp C, density 1.52 GM/CC, with a case weight of 500 grams and a charge weight of 125 grams.

Solution:

Step 1 - By definition C = 125 and M = 500 so connect M and C on the nomogram and read C/M = 0.25.

Step 2 - Using both C/M scales for alignment purposes, locate the point A on the curve.

Step 3 - Find the point A on the $((C/M)/ (1 + C/2M))^{1/2}$ scale below the curve. (The scale above the curve may be used for alignment of the point A).

Step 4 - From Table 2-7, $(2E)^{1/2}$ = 7140 for pressed Comp C loaded At 1.52 GM/CC.

Step 5 - Connect the value found in (3) above with 7140 on the $(2E)^{1/2}$ scale and read V_o = 3400, the initial fragment velocity.

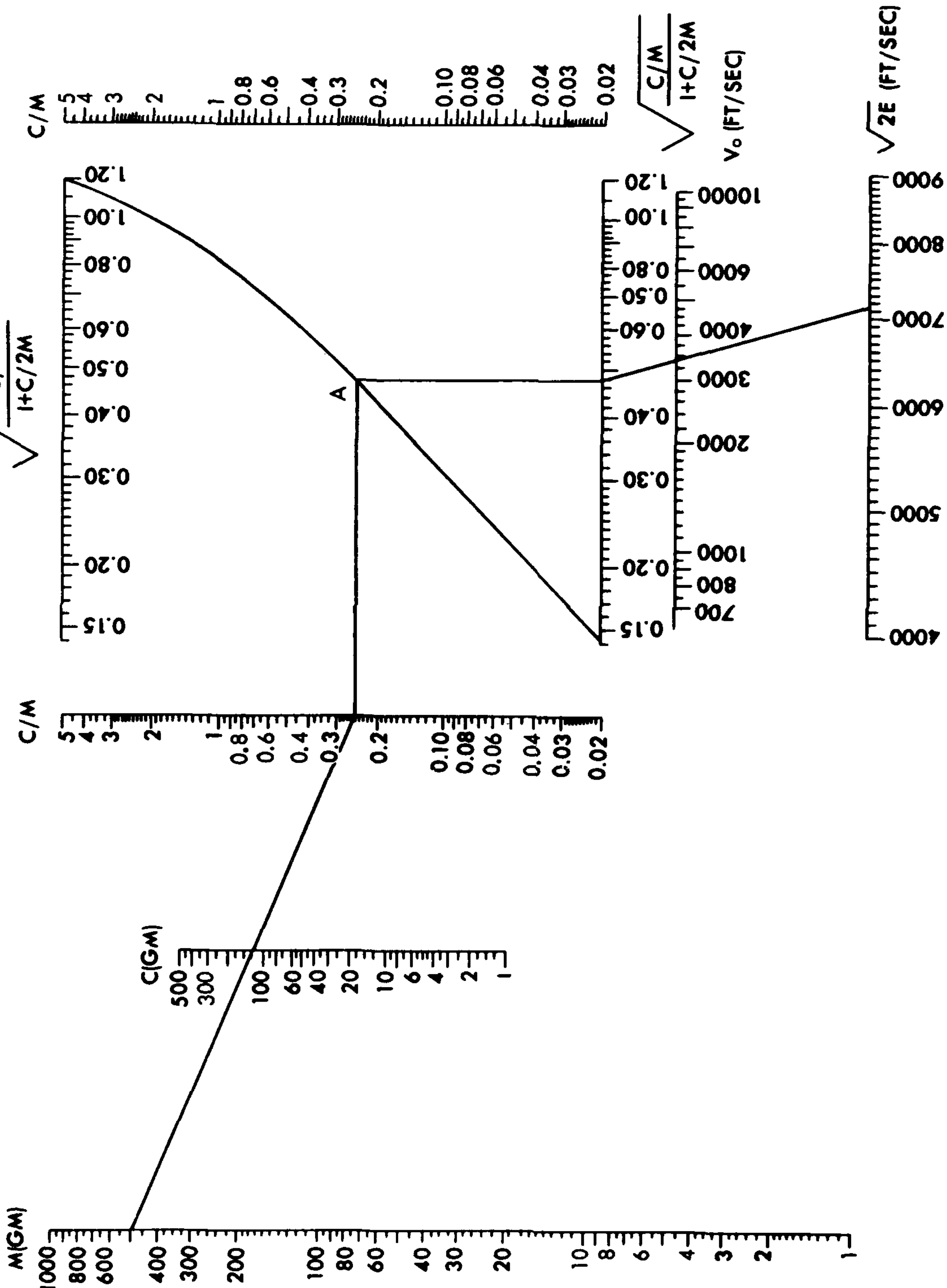


Figure 2-27 Gurney Law for Initial Fragment Velocity

Figure 2-28

Striking Velocity of a Fragment

The velocity, V_s with which a fragment strikes a target distance R away from an exploding missile is a function of the fragment's initial velocity, mass, and average presented area, and its height above sea level. The striking velocity (also called retarded velocity) is found from the following equations:

$$V_s = V_o e^{-kR} \quad \text{and} \quad k = K_D \, A/m \, \rho_a$$

where:

V_s = Striking velocity (ft/sec)
V_o = Initial velocity (ft/sec)
R = Distance traveled (CM)
K_D = Drag coefficient
A = Average presented area (CM^2)
m = Mass (GM)
ρ_a = Density of Air (CM/CC)

The three factors required for calculating k are shown in the Table (A) and graphs of Figure 2-28. (Here, m is shown in oz and R in ft, since these units are most frequently used.) C_O was computed from temperature data by the equation: $C = C_O (1 + T/273)^{1/2}$. A constant value of $K_D = 0.4$ rather than the K_D obtained from Graph (C.2) is a suitable approximation for many purposes. In Graph (D), V_s/V_o is shown as a function of k and R; this ratio times the initial velocity yields the striking velocity. The use of these graphs for steel fragments is demonstrated in the following example:

Example:

Find the velocity with which a 1/8 oz spherical steel fragment from a weapon detonated at a height of 10,000 ft will strike a target 120 ft away, if the fragment's initial velocity is 4000 ft/sec.

Solution:

Step 1 - From Table (A), read A/m = 0.202 for a 1/8 oz fragment.

Step 2 - From Graph (B), read ρ_a = 0.00087 GM/CC at 10,000 ft.

Step 3 - From Graph (C.1), the velocity of sound, C = 1094 at 10,000 ft, the Mach No. C/C_o = 3.66 and from Graph (C.2) the corresponding K_D for a spherical fragment is 0.367.

Step 4 - Then $k = 6.45 \times 10^{-5}$, and from Graph (D), at 120 ft, $V_s/V_o = 0.79$.

Step 5 - The striking velocity = 0.79×4000 = 3160 ft/sec.

References:

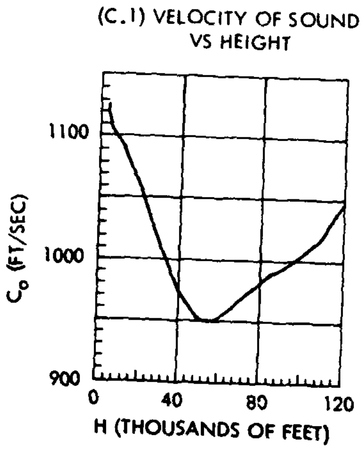
Table A - (Reference 25)

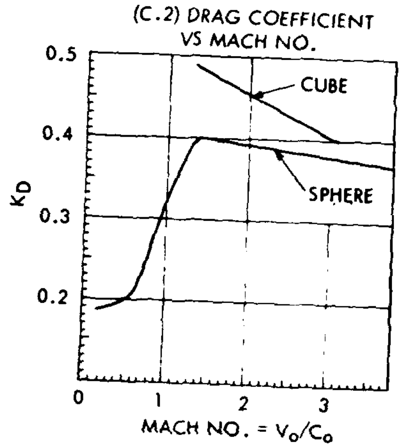
Graphs B and C.1 (Reference 26)

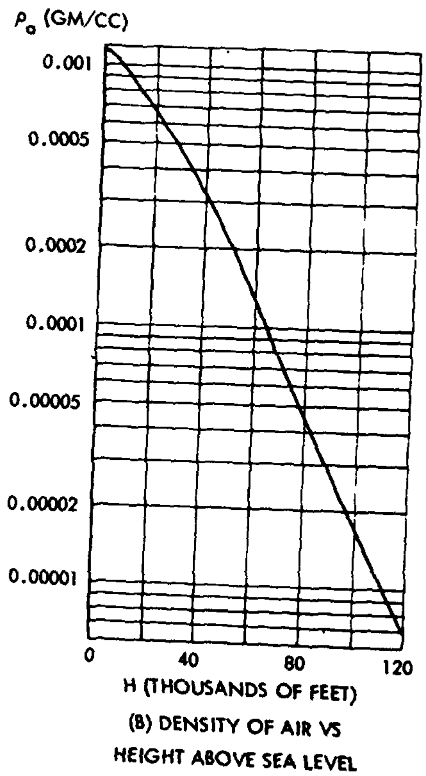
Graphs C.2 and D (Reference 27)

TABLE (A)
STEEL FRAGMENTS
PRESENTED AREA/MASS (A/m)

MASS (OZ.)	SPHERE (CM^2/GM)	CUBE (CM^2/GM)
1/8	0.202	0.250
1/4	0.160	0.199
1/2	0.127	0.158
1	0.101	0.125







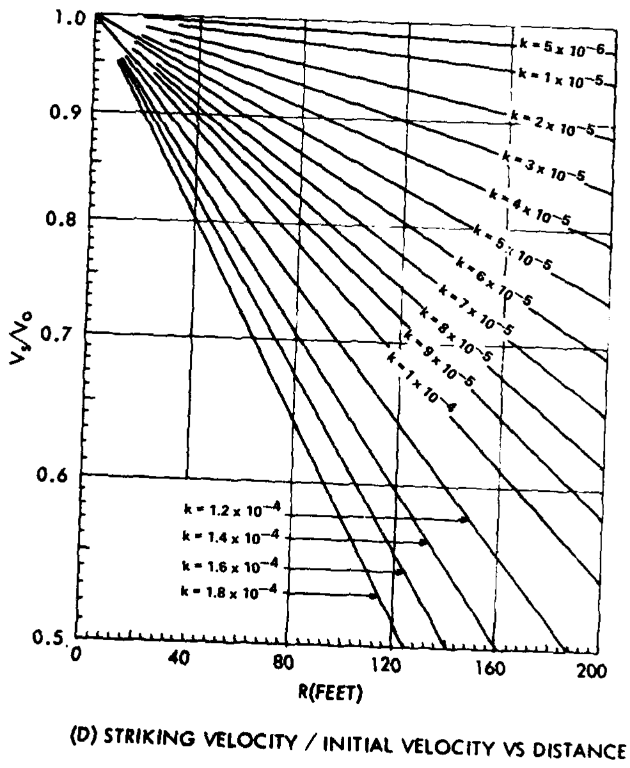


Figure 2-28 Striking Velocity of a Fragment

Figure 2-29

Depth of Penetration of Mild Steel

versus Striking Velocity

Demarre's Empirical Equation for Computing the Depth of Penetration of Irregular Fragments into Mild Steel is:

$$P = C(m)^{1/3} (V/1000)^{4/3}$$

where:

C = 0.112 for mild steel
m = mass in ozs
V = striking velocity in ft/sec

The graph following is a plot of the depth of penetration versus velocity for fragments of weight ranging from 1/128 to 8 oz. (Reference 28)

Example:

A fragment of 1/20 of an oz at 5000 ft/sec can perforate up to about 0.37 in. of steel plate.

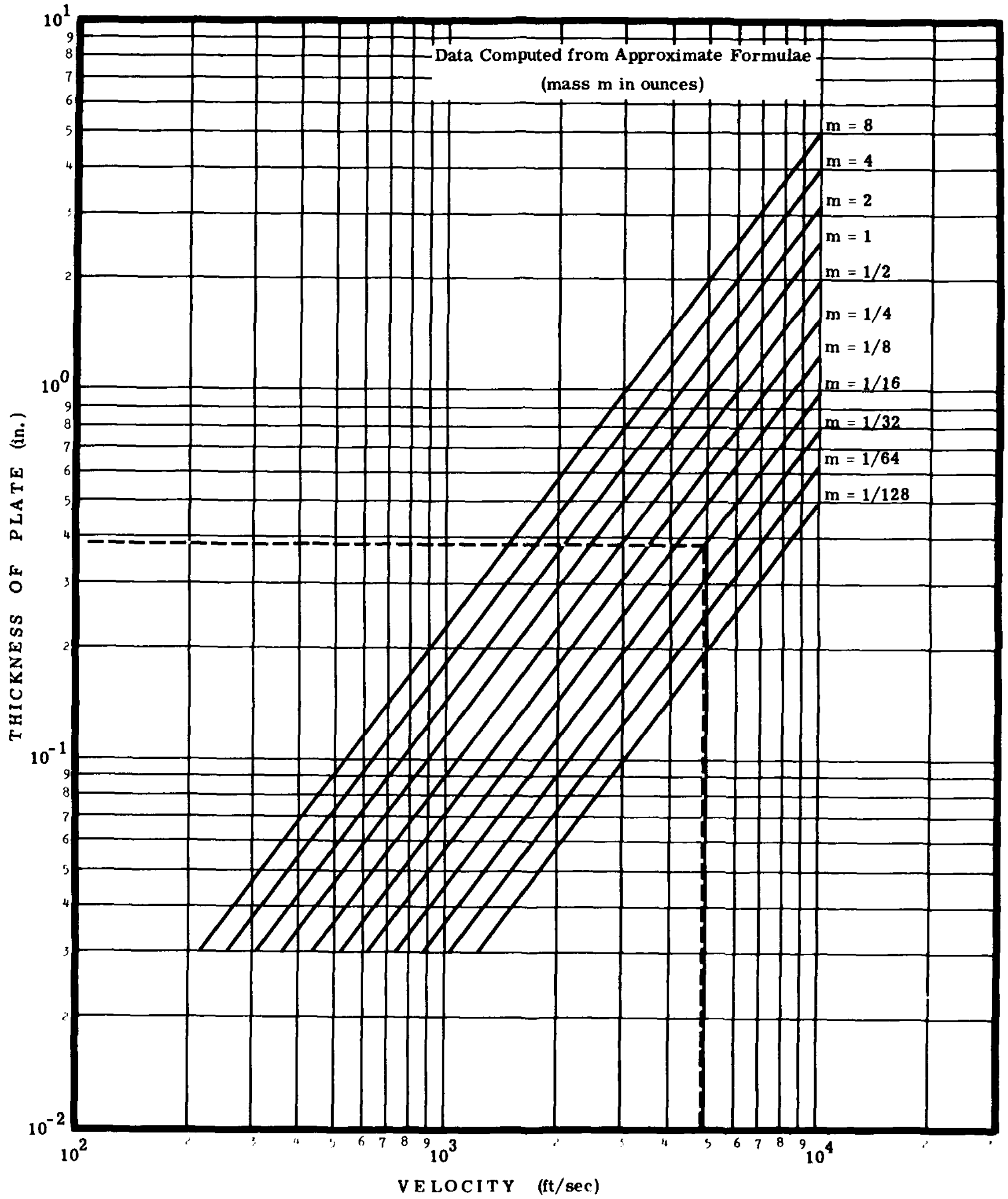


Figure 2-29 Depth of Penetration of Mild Steel versus Striking Velocity (Reference 28)

Figure 2-30

Initial Velocity of Fragments versus the Horizontal Distance in the Super-Sonic Range

From Figure 2-30 for a particular initial velocity and fragment mass combination, read the distance along the fragment trajectory on the abscissa. This distance represents the super-sonic portion of the trajectory, which is assumed to be straight. (Reference 29)

Figure 2-31

Horizontal Distance of Fragments in the Sub-Sonic Range

The sub-sonic horizontal range is read on the abscissa of Figure 2-31 corresponding to particular combinations of fragment mass and initial angle. Addition of the sub-sonic and super-sonic parts of horizontal range will yield maximum horizontal range.

Example:

Given: A fragment weighing 2.05 oz with an initial velocity of 4000 ft/sec. On Figure 2-30 at 4000 ft/sec velocity trace a perpendicular line to the ordinate at 4000 ft/sec to the intersection with the curve for the 2.05 oz fragment. At intersection read the value of 420 ft at the abscissa for the super-sonic range. Figure 2-31 gives the maximum horizontal distance for the 2.05 oz fragment (initial angle of 20 degrees) of 1230 ft. Addition of the super-sonic portion (420 ft) and the subsonic portion (1230 ft) gives a maximum horizontal distance of 1650 ft.

Find: The maximum horizontal distance for the fragment if it begins its travel at an angle of 20 degrees.

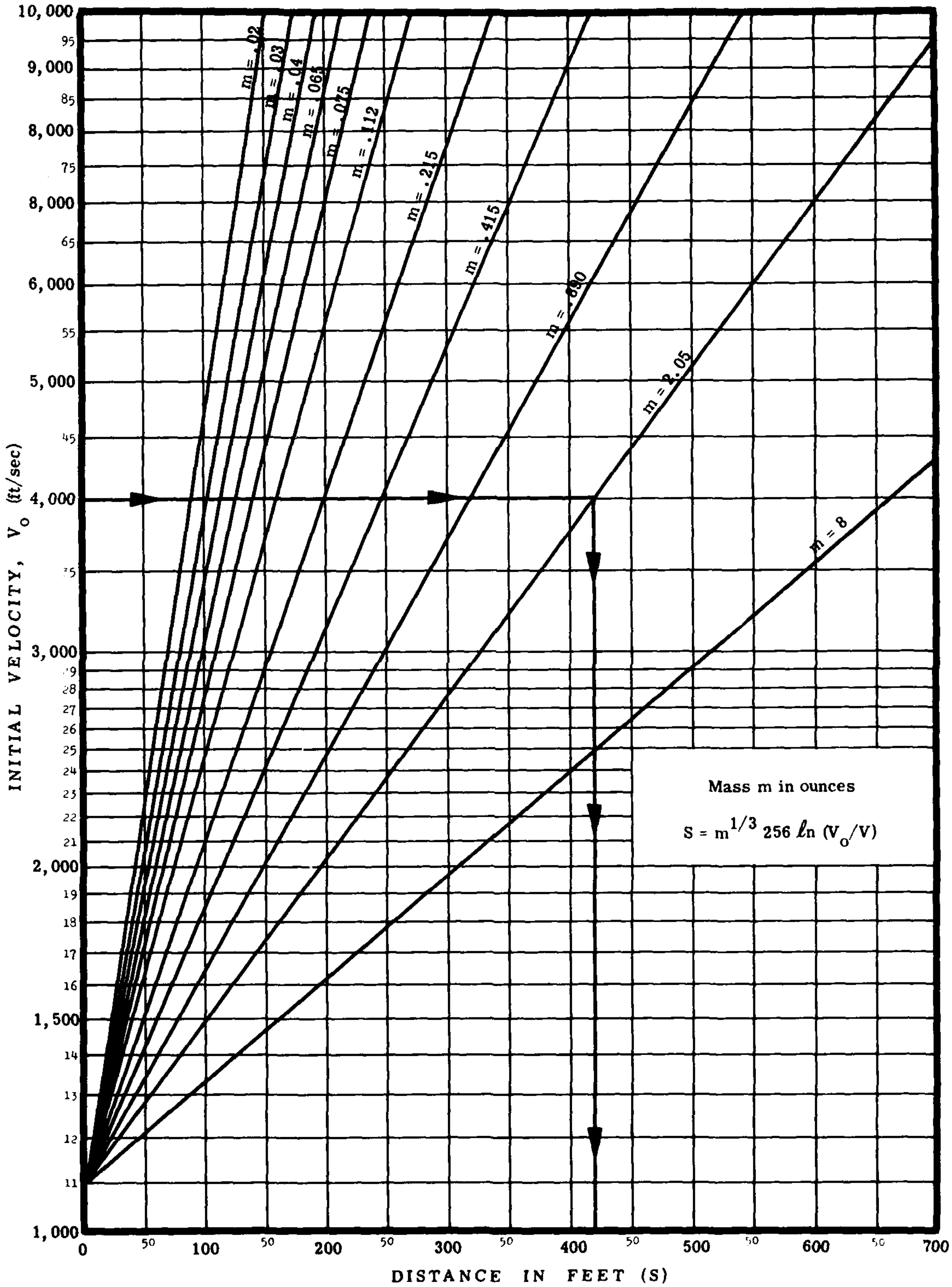


Figure 2-30 Initial Velocity versus Horizontal Distance

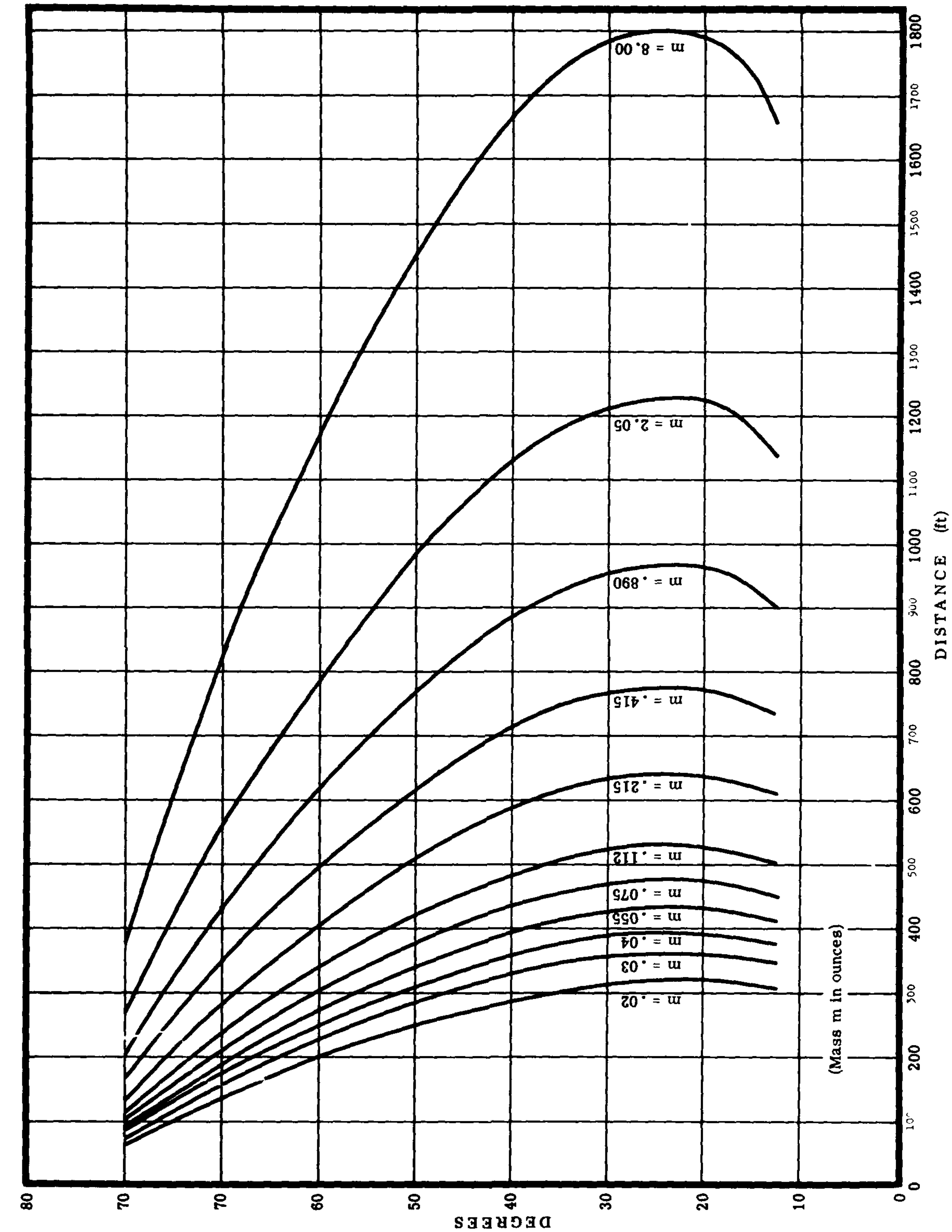


Figure 2-31 Horizontal Distance of Fragments in the Sub-sonic Range

It follows that if this early ignition is credible and predictable, the explosive yield can be expected to be far lower than that anticipated after a more complete mixing of all available propellants.

2-5.3.2 Fragment Radius. Referring again to Table 2-9 and Figure 2-35, the reader may gain some insight as to the way in which simulated ballistic and non-ballistic fragments are transported by the turbulent zone below the flame of a deflected S-IC plume in a static test. Also from Table 2-8 and Figures 2-23 and 2-34 it may be noted that the average fragment density outside the major fragment radius (let us say 85% by weight or number) is about 0.3 fragment per 10,000 square feet or 1 fragment per acre for the Atlas Centaur, the S-IV-ASTV and PYRO-275 tests. Note also that 100% of the fragments found, from all of the incidents described, fall within 1500 feet of the vehicle/missile.

Note: Next text found on page 2-67.

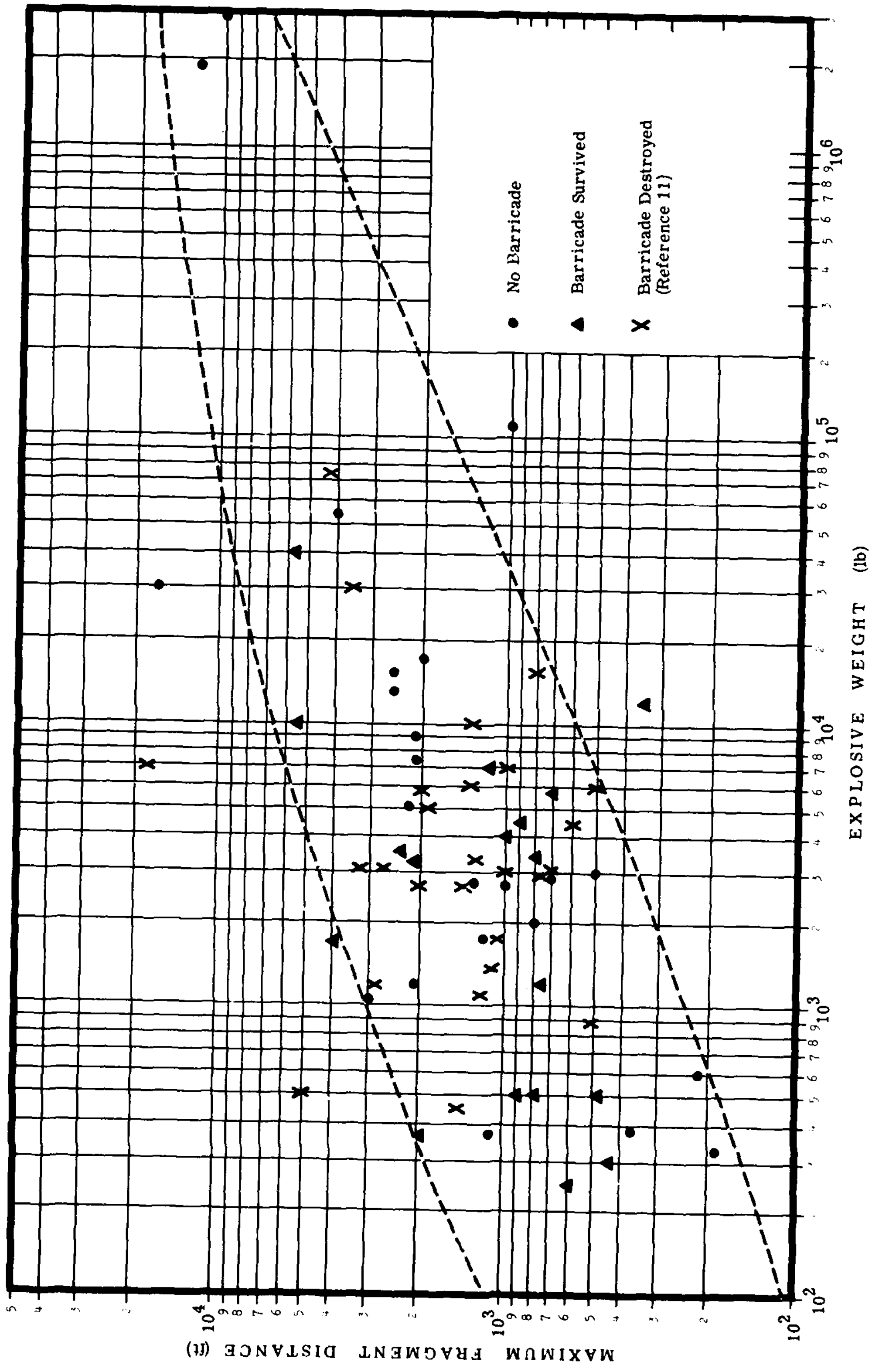


Figure 2-32 Explosive Weight versus Maximum Fragment Distance for Accidental HE Surface Bursts

Table 2-8

Fragment Data from Selected Space Vehicle Explosions

Vehicle Site/Date	Propellant/ lb	Yield TNT (%)/lb	Incident	Number of Fragments/ Weight, lb	Source	Major Fragment Radius, ft	Average Fragment Density/10,000 ft^2 Outside Fragment Radius
S-IV - ASTV Douglas-Sacramento 1-24-64	LO_2/LH_2 100,000	(1%) 1,000	Explosion Overpressurization of LOX tank to 100 psia.	262 Total 44 Wt'd 1,882	Investigation of S-IV Vehicle explosion by J. B. Gayle	400	.31
Atlas Centaur KSC 3-2-65	LO_2/LH_2 30,000 LO_2/RP-1 172,000 Total 284,000	(0.75%) 1,930	Launch At T 1.1 sec. the booster engine cutoff at T 1.63 vertical vel. = 0. *Vehicle fell back* bursting the booster tanks.	40 9,085	Investigation of the Atlas Centaur Vehicle explosion by S. S. Perlman	400	.29
S-IV - EAFB Edwards 7-14-65 Test Vehicle Run 062	LO_2/LH_2 91,000	(3.5%) 3,200	Induced failure 18 in. ram on inter-tank bulkhead.	412 3,125	Project PYRO Quarterly Progress Report 9/65	500	.5
S-IVB-503 Douglas-Sacramento 1-20-67	LO_2/LH_2 231,000	(1%) 2,300	Explosion On repressurization Wrong type welding rod, titanium spheres.	166 1,426	Report of Investigation S-IVB-503 Incident 1-20-67 by Kurt B. Debus, KSC	600	.81
PYRO-275 (Test Tanks) AFRPL Edwards 3-22-67	LO_2/RP-1 25,000	(4%) 1,000	Tank rupture Self-ignition after 500 milliseconds of mixing.	60 1,628	Project PYRO Reports 3-67, 6-67	500	.30

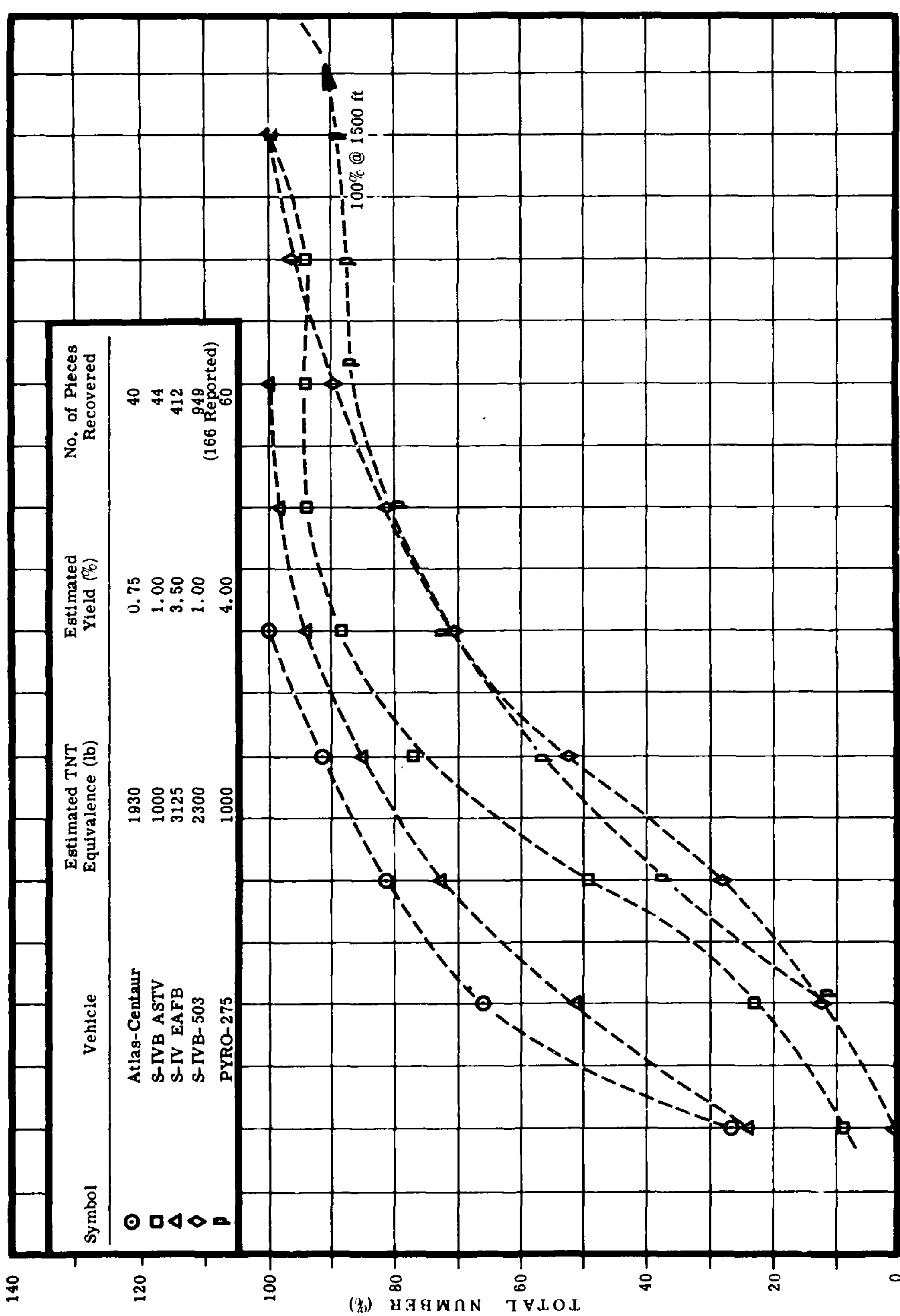


Figure 2-33 Percentage of Total Number of Vehicle Fragments within Range Indicated

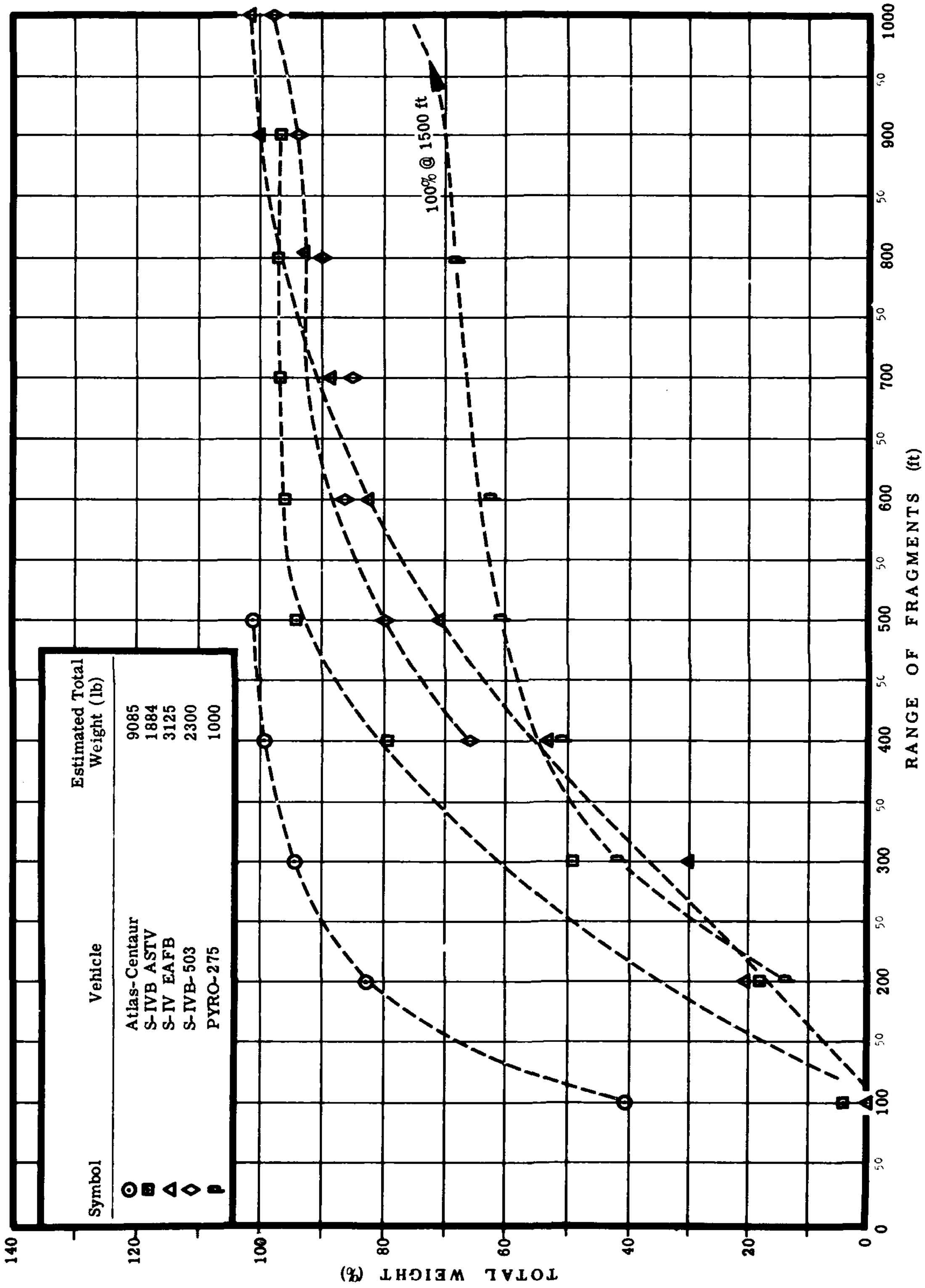


Figure 2-34 Percentage of Total Weight of Vehicle Fragments within Range Indicated

Table 2-9

Fragment Distribution of S-IC Flame Plume Environmental Study
(Data for Figure 2-35)

Item Number	Description and Location	Weight, lb	Area, ft^2	Range, ft	Assumed C_d	C_dA/W	Velocity, ft/sec
1	WC-1-1	0.67	0.085	140	1.6	0.02	900
2	WC-2-2	0.9	0.085	40	1.6	0.2	
3	SC-1-1	0.4	0.1	150	0.4	1.0	
4	SB-2-2	0.025	0.05	80			
5	SC-2-3	0.04	0.1	100		2	
6	WB-3-2	0.4	0.05	30	1.6	0.33	
7	2"FC-3-L	3.6	3.1	20			
8	FSq-3-L	1.1	1.0	30			
9	4FSp-3-L	2.3	2.0	10			
10	S Sq-3-L	0.2	0.83	100			
11	SB-3-1	0.025	0.05	50			
12	WB-3-1	0.4	0.5	40	1.6	0.024	40
13	SB-3-2	0.025	0.05	50			
14	2"FC$_L$-3-L	3.6	3.1	20			
15	3'FSq-3-L	1.7	0.5	50			
16	SB-2-1	0.025	0.06	60			
17	16"FC$_L$	1.6	0.4	90			
18	FT-3-L	3.6	0.1	150			
19	2"FC$_L$-3-L	3.6	0.1	70			
20	WB-1-1	0.34	0.05	320	1.6	0.024	130
21	2'FSp3-L	1.6	1.0	70			
22	S Sq-3-L	0.2	0.83	100			
23	16"-FC$_L$	1.6	1.4	150	0.8	0.7	
24	FT-3-L	3.6	3.1	150			
25	2'FS-3-L	2.3	0.7	170	1.3	0.4	350
26	FSp-3-L	1.1	1.0	180	0.88	0.8	
27	4'-FSp-3-L	2.3	1.8	400		0.3	
28	SC-1-2	0.04	0.1	700	0.4	1.0	
29	2'FSp-3-L	1.6	0.62	600	0.77	0.3	
30	8"FC$_L$-3-L	0.41	0.35	150			

LEGEND:

Code for Description of Fragments and Mounting Location

I. Type Material

W - Wood
S - Styrofoam
S$_F$ - Styrofoam (fused)
F - Fiberboard

II. Configuration

B - Ball
C - Cube
S - Sheet
C$_L$ - Circle; preceding number indicates diameter
T - Triangle
Sp - Strip; preceding number indicates length
Sq - Square

III. Fragment Launching Pole Numbers and Locations

Pole 1 - 450' from face of test stand on center line (C. L.) of flame bucket, which faces north.
Pole 2 - 550' from face of test stand and 25' east of C. L. of bucket
Pole 3 - 650' from face of stand on C. L. of flame bucket
Pole 4 - 550' from face of stand, 100' east of C. L. bucket
Pole 5 - 550' from face of stand, 100' west of C. L. bucket

IV. Fragment Elevation on Poles

1 - 80' level
2 - 60' level
3 - 40' level
4 - 20' level
L - 40' level Pole 3, steel wire between guy wires for hanging fragments

Examples:
WC-1-2 = Wood, Cube, Pole 1, 60' level
F-T-3-L = Fiberboard, Triangle, Pole 3, Line 40' level

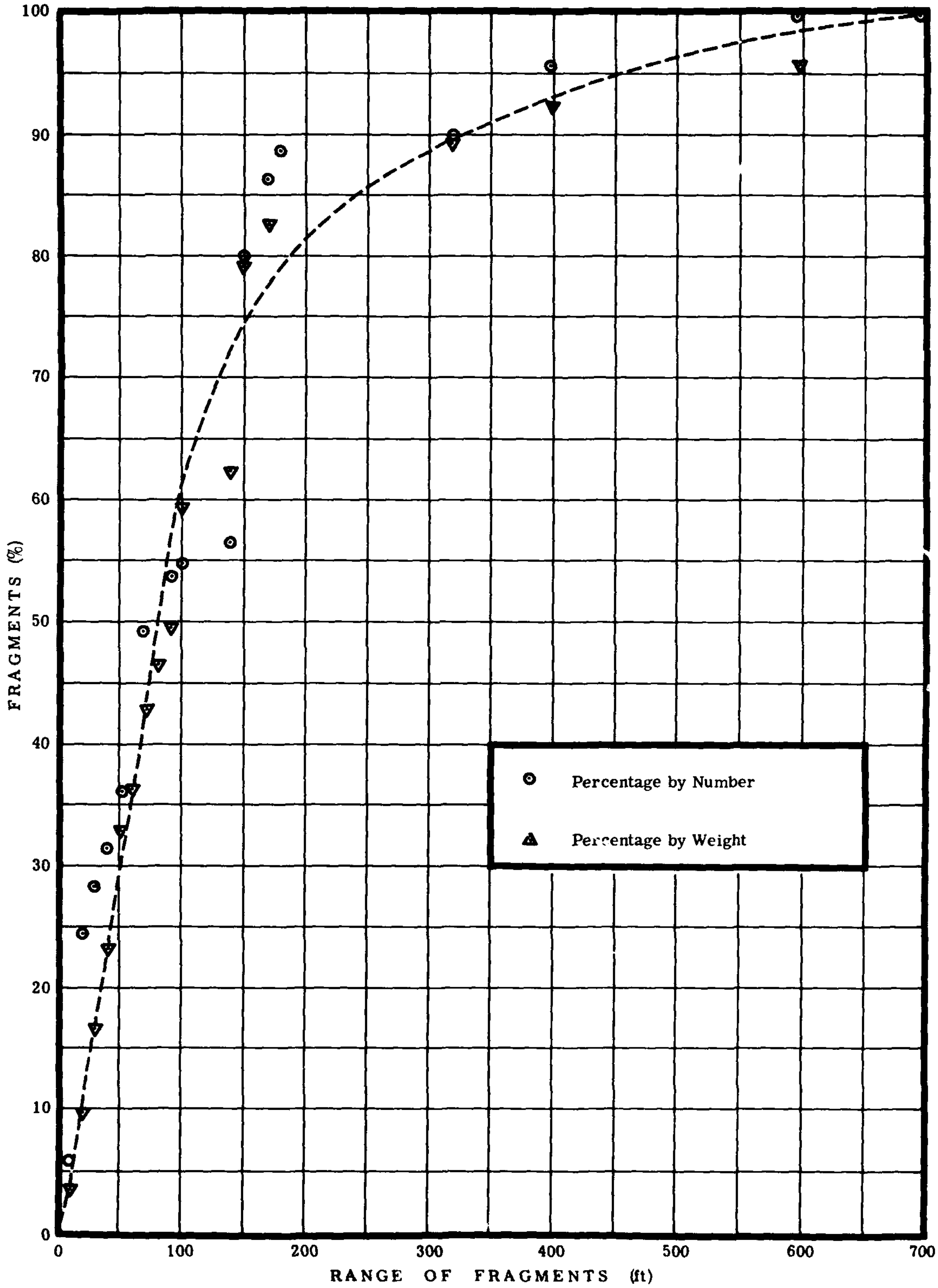


Figure 2-35 Fragment Distribution of S-1C Flame Plume Environmental Study

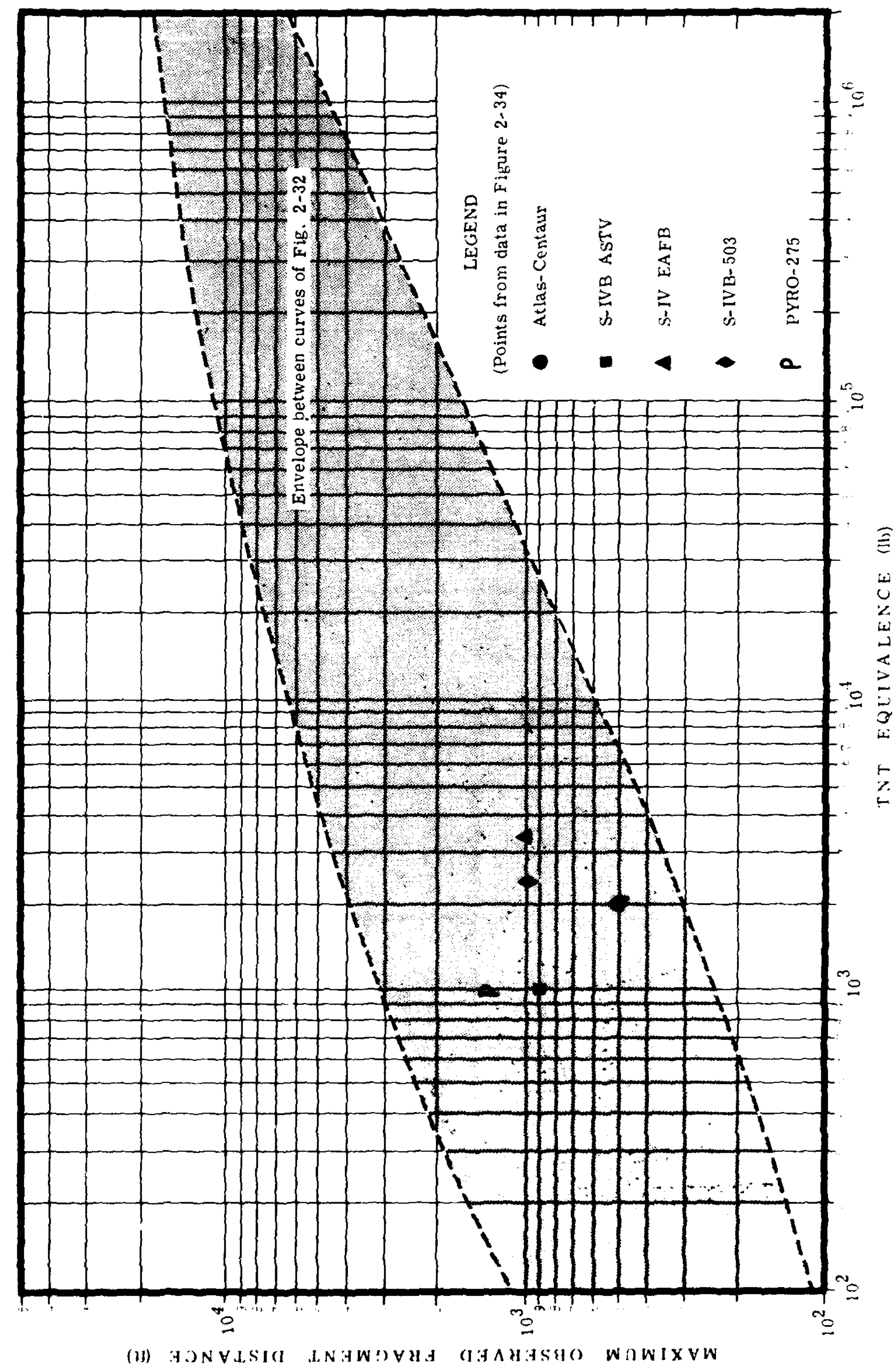


Figure 2-36 Estimated TNT Equivalence versus Maximum Fragment Distance for Actual Space Vehicle Explosions

2-6 FIREBALL EFFECTS AND DAMAGE (reference 30).

Gayle and Bransford have derived empirical expressions for the dimensions and duration of a fireball associated with an explosion of liquid bipropellants. Their expressions and theory serve as the basis for some further work by URS on cryogenic propellant testing in the Project PYRO experiments reported herein.

Equation 2-4 of Gayle and Bransford relates the fireball dimension in terms of equivalent diameter D, in feet, to the total propellant (fuel plus oxidizer) weight W, in pounds, for the propellant combinations $LO_2/RP\text{-}1$, LO_2/LH_2, $LO_2/RP\text{-}1$ and LH_2, and N_2O_4/N_2H_4 - UDMH (50: 50):

$$D = 9.56\ W^{0.325} \qquad \text{Eq. 2-4}$$

The estimated standard error in D is $\pm$ 30 percent and it must be noted that D is an equivalent diameter (by definition). The equation does not always provide an accurate (to $\pm$ 30 percent) indication of the maximum dimension(s) of the fireball because some of the fireball observations used to derive the empirical relation were markedly asymmetrical. Attempts were therefore made to estimate an "equivalent spherical diameter." The magnitude of the departure from the diameter given by equation 2-4 is indicated by data from an actual Titan test that involved 100,000 pounds of $LO_2/RP\text{-}1$; wherein the maximum fireball horizontal dimension was estimated to be from 800 to 1000 feet, while equation 2-4 yields an equivalent diameter of approximately 400 feet.

Again from Gayle and Bransford, the fireball duration τ, in seconds, during which hazardous temperature levels exist is given by:

$$\tau = 0.196\ W^{0.349} \qquad \text{Eq. 2-5}$$

where the standard error in the duration is 84 percent, excluding the time attributable to residual fires of scattered or pooled propellants as a result of surface depressions or structural confinement.

2-6.1 PROJECT PYRO FIREBALL EFFECTS. This section was extracted from URS Report 652-35 (reference 13) in order to give the reader an insight into the problem of heat transfer hazards from liquid propellant explosions. The detailed final report is suggested for further study. Only the primary fireball effects are discussed here; an evaluation of thermal hazards external to the main body of the fireball are given in section 6, Vol. I of reference 13.

Eleven 25,000 pound tests, five of $LO_2/RP\text{-}1$ and six of LO_2/LH_2, were conducted during Project PYRO experimental work. Figures 2-37 and 2-38 are given to obtain the heat flux density as a function of time for measurements fixed at the 25,000 pound weight level and observed by instruments which are fixed in space, i.e., they could not observe any motion or rise of the fireball. The data presented are associated only with a 25,000 pound sample. Equation 2-6 gives the fireball duration τ_0 in seconds as a cube root function of the propellant weight:

$$\tau = CW^{1/3} \qquad \text{Eq. 2-6}$$

Where the value of C is 0.113 for $LO_2/RP\text{-}1$ and 0.077 for LO_2/LH_2.

Figures 2-37 and 2-38 each present two curves. One is the "bounding curve" which is an estimate of the upper bound of the heat flux density based upon the eleven tests. The "recommended curve" is superimposed upon the "bounding curve" until the time τ_0, given by Equation 2-6, at which point in time the heat flux density decreases to zero.

According to the authors of the PYRO final report, the "recommended curves" presented implicitly contain the constraint that the probability of exceeding the cumulative heat flux density between the limits of $t = 0$ and $t = \tau_0$ is 1 percent. Further, the variation of the heating pulse with weight of propellant follows the implicit scaling contained in Equation 2-6 and that the heat flux density at a scaled time, using this cube root scaling, will be invariant with any variation in propellant weight. The latter statement is based upon the measured invariance of fireball temperatures from scale to scale (typically 2300°K).

The heat flux density measurements upon which Figures 2-37 and 2-38 are based were obtained at locations no closer to the "center of explosion" than about one-fifth of the fireball radius and it might be expected that heat transfer rates at the center and during the first small fraction of the duration could be more severe than those indicated by the curves. Specifically, about 0.1 to 0.2 inch of a solid aluminum structure was ablated from the surface at the central explosion region during the 25,000 pound test series. This suggests heat flux densities of the order of 1,000 watt/cm^2 for the limited time available. For details of the experimental equipment, the aluminum structure and its ablation see appendix C, Volume I of reference 13.

Data for hypergolic systems is extremely limited for the purpose of evaluating heat flux density. Examination of data available suggests that the heat flux density is somewhat less in magnitude than the "bounding curves" of either Figure 2-37 or 2-38 but that the duration, τ_0 is likely to be longer. Similarly, the use of presented data from Figures 2-37 and 2-38 and equation 2-6 for quantities above 25,000 pounds was recommended but the curves will be somewhat conservative in the hazard estimate. For extrapolation to significantly lesser weights, i.e., 1000 pounds (μ less) the τ_0 as given by equation 2-6 should be increased by multiplying factor of 1.2 and 1.6 for $LO_2/RP\text{-}1$ and LO_2/LH_2 respectively.

2-6.2 PROJECT SOPHY FIREBALL EFFECTS. The objectives of Project SOPHY have been previously discussed in Section 2-4.7.1. Fireball data were recorded and reduced from a total of 16 tests made using right circular cylinders of propellant placed on the surface, on end, with diameters varying from 11 to 72 inches and length 4 times the diameter.

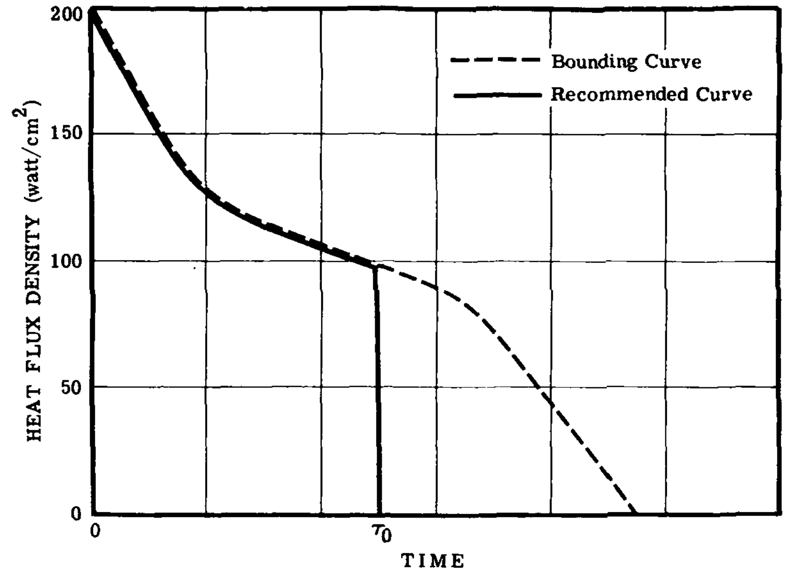


Figure 2-37 Bounding and Recommended Heat Flux Density Curves for the LO_2/RP-1 Propellant Combination

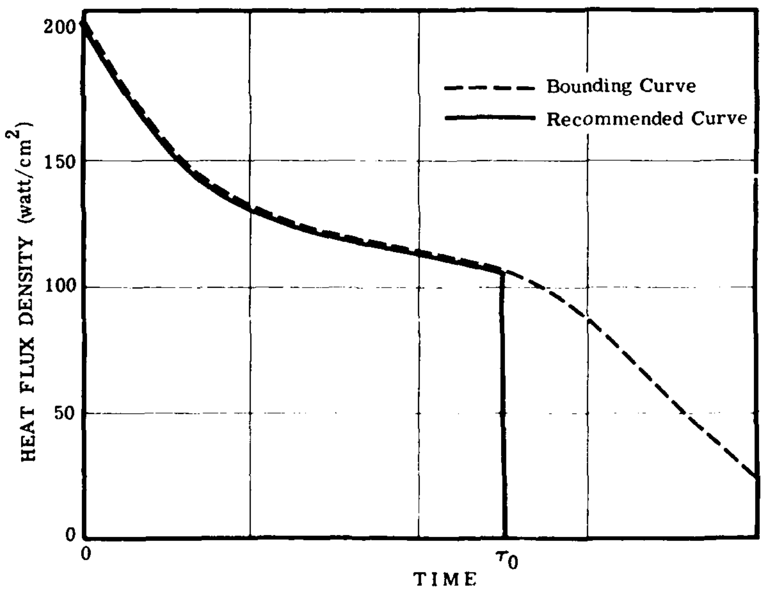


Figure 2-38 Bounding and Recommended Heat Flux Density Curves for the LO_2/LH_2 Propellant Combination

Fireball history plots were made for each test, using a Cal-Comp plotter. These graphs showed both the height and diameter of the fireball as a function of elapsed time after detonation. Fireball diameter was taken to be the maximum horizontal dimension of the fireball; fireball height was the maximum vertical dimension of the fireball, not the height of the fireball above the ground. While the exact shapes of these plots differed considerably from test to test there were certain similarities. In every case, both the height and diameter of the fireball increased rapidly to a maximum value, or plateau. However, the fireball-decay pattern differed markedly from test to test. It was decided to characterize the fireball size and rate of growth by five parameters: These were:

a. Maximum fireball height

b. Maximum fireball diameter

c. Time to maximum height

d. Time to maximum diameter

e. Total duration of the fireball

The summary values for the 16 tests are presented in Table 2-10. This table also shows the test result (go or no-go), sample diameter, weight fraction RDX, and total sample weight (propellant weight plus booster weight) for each test. Total sample weight had to be used since it was impossible to isolate that portion of the fireball due to the propellant from that due to the TNT. (References 15 and 31)

It must be remembered that the SOPHY tests were basically propellant critical diameter and critical geometry studies and a TNT booster was utilized to initiate detonation. The test result terms of go and no-go refer to a sustained detonation and fading detonation respectively. The go or no-go condition was determined as follows:

The criterion for sustainment of detonation wave velocity was the stabilizing of the velocity of the wave at some essentially constant value after the high-velocity detonation wave from the booster had decayed in the first half of the charge. Although minor fluctuations of the successive data points were usually observed in a sustained detonation, there was no difficulty in distinguishing this behavior from the fading detonation wave in a subcritical sample.

Review of the data shows there is no effect of test result (go or no-go) upon the fireball parameters. This may be explained by the fact that in each test approximately 1/5 of the total sample weight was composed of TNT, and even in the cases of no-go's, the major portion of the propellant was involved in a fading detonation, contributing to the fireball as the detonation wave attenuated.

In reviewing this data, it must be remembered that the fireball characteristics of the propellant detonation are for propellant formulation ANB-3226 with a weight fraction for total oxidizer of 69% and aluminum of 15%. However, this is a representative formulation and many other composite formulations contain approximately the same weight fractions of oxidizers and aluminum, so that estimates that could be made from this data should be relatively accurate.

Table 2-10

SOPHY Fireball Data

Test Number	Test Result	Diameter (in.)	Weight Fraction RDX	Total Sample Weight (lb)	Maximum Fireball Height (ft)	Maximum Fireball Diameter (ft)	Time to Maximum Height (msec)	Time to Maximum Diameter (msec)	Total Fireball Duration (msec)
CD-79	No-go	11	0.0475	353	48	85	300	50	950
CD-80	Go	12	0.0475	467	50	93	300	50	1200
CD-81	Go	18	0.034	1,531	75	160	400	350	2000
CD-82	Go	24	0.029	3,545	85	185	450	75	1250
CD-83	Go	27	0.034	4,951	100	225	850	95	2400
CD-84	Go	24	0.034	3,558	100	195	600	80	1800
CD-85	No-go	23.5	0.018	3,903	120	190	750	500	3400
CD-86	Go	23.5	0.024	3,909	125	212	750	75	2700
CD-88	No-go	44	0.00	13,715	210	300	1000	750	2900
CD-89	Go	48	0.0073	27,704	150	380	750	112	2250
CD-90	Go	48	0.0050	27,834	200	380	1000	112	2500
CD-91	No-go	11	0.0175	353	60	95	350	75	1170
CD-92	No-go	48	0.0025	27,846	218	330	1400	250	4300
CD-93	Go	13	0.06	580	48	116	420	40	1500
CD-96	Go	72	0.00	92,000	325	480	1500	250	4300
CD-98	No-go	60	0.00	53,500	300	400	1500	370	4250

2-7 GROUND SHOCK EFFECTS AND CRATERS

2-7.1 SEISMIC DISTURBANCES. Ground vibration of seismic waves are generated by varying sonic or mechanical pressures on the earth's surface. During an engine firing or an accidental explosion, the ground vibration generated locally at the surface by the traveling pressure wave can be expected to be predominant over any mechanically excited ground vibration except in the immediate vicinity of the source. Once the local coupling between this sonic pressure and the ground motion is defined, the spreading and attenuation losses of the sonic pressure field itself (i.e., engine noise or blast wave), as discussed in Chapter 7, will define the "propagation losses" of this locally generated ground motion.

2-7.1.1 Sonically Coupled Ground Motion. Experimental measurements of ground motion from high energy explosions have demonstrated that the strongest component of motion coincides approximately with the arrival of the blast overpressure (reference 32). The arrival of the ground wave lags slightly behind the air shock for blast overpressures greater than 10 psi. At lower overpressures, the two arrival times are essentially identical.

Similar observations have been made for the strongest ground motion associated with rocket noise from launch and static firings of the Saturn S-1 booster (references 33-36). In this case, the observed arrival times for the strongest ground motion and peak sound pressure corresponds to the velocity of the sonic pressure wave.

These results have led to the choice of a simple one-dimensional theoretical model to explain, to a first approximation, the observed ground motion. In other words, the local motion of the ground surface, subjected to a traveling pressure wave is assumed to be that of a semi-infinite elastic medium subjected to a stationary but time-varying pressure load (references 37-38). While this simple model represents a gross simplification of the true situation, its application is consistent with the scatter in experimental data and lack of detailed knowledge of the seismic properties of the ground in a given location. The essential result predicted by this analytical model is that the peak vertical ground velocity V_p at the surface is given by the equation for the particle velocity of a plane "acoustic" wave as:

$$V_p \simeq P_p/\rho c_d \qquad \text{Eq. 2-7}$$

where

P_p = peak sonic pressure (peak side-on overpressure for blast wave or peak sound pressure for acoustic wave)

ρ = mass density of soil

c_d = effective seismic velocity for dilatational or compression waves in ground

It can be anticipated that this expression will underestimate the true ground velocity. Since the propagation velocity of the traveling pressure wave will be of the same order of magnitude as the velocity of seismic waves near the surface, a dynamic amplification effect may be expected. Although useful theoretical models have been developed which include this effect (e.g., reference 37), lack of detailed knowledge of seismic characteristics of local soil structure make it difficult to apply such theories at this time.

Fortunately, sufficient experimental data are available so that an empirical expression can be defined which relates peak surface velocity to peak sonic pressure. This is given by:

$$V_p = K \cdot P_p \qquad \text{Eq. 2-8}$$

where K is an experimentally determined constant.

This simple method is based on a remarkably consistency for the available experimental data from reference 32-38, which indicates that the average value of K falls in the range of 0.8 to 1.2 in./sec/psi and has a maximum value of about 1.5-2 in./sec/psi.

2-7.1.2 Criteria for Hazardous Seismic Disturbances. A criteria for structurally damaging ground motion has been established from extensive correlation of building damage from blasting operations (reference 39). An approximate lower bound for the threshold of light damage to building structure is a peak ground velocity of 2 in./sec. Thus, assuming the maximum value of 2 for the proportionality constant K in the above expression, a peak blast overpressure of 1 psi could generate potentially damaging seismic disturbances. This is above the threshold of directly induced blast damage from the overpressure on a building. Thus, in most cases, propellant blast-induced seismic disturbances would not be as hazardous as the direct air-blast effects.

2-7.2 CRATERS. When a detonation occurs at or near the surface of the ground a crater is formed (see Figure 2-37). The size of this crater depends on several factors:

a. The energy released by the explosive

b. the position of the explosive relative to the surface

c. the ground material type

d. gravitational effects

e. the shape of the charge

f. the coupling of the charge to the ground

The influence of the energy release is obvious; that is, the larger the charge and the more powerful the charge, the larger the crater. As the distance between the explosion and the surface is increased, the cratering effects become smaller. As the charge is placed deeper in the ground, the size of the crater increases, both in radius and depth, until a maximum is reached after which the crater size will decrease with increasing depth of burial (DOB). However, as the air space around the charge becomes larger (the charge is loosely coupled to the ground) the crater dimensions become smaller. For deeply-buried explosions, i.e., when the explosion is contained, no crater is visible. The greater the containing material's strength and energy-dissipative properties, the smaller the crater size will be. The size of the apparent crater is affected by gravity in the amount of the fall-back material, that is, the material originally ejected which returns under gravity to the crater zone (reference 40).

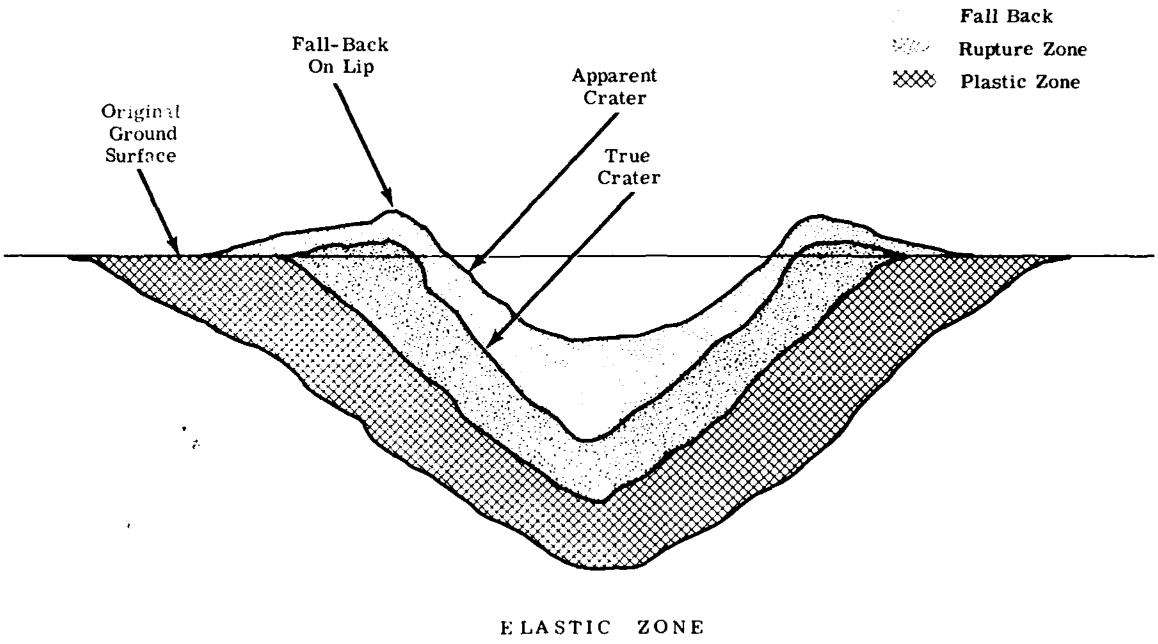


Figure 2-39 Typical Crater Profile

2-7.2.1 Crater Dimensions. Crater radius (or diameter) and depth usually are of interest. Figure 2-40 shows the scaled apparent crater radius as a function of scaled depth of burst and type of ground in which the explosion takes place. Apparent crater depth as a function of depth of burst and ground material is given in Figure 2-41.

2-7.2.2 Crater Ejecta from Surface Bursts. The material thrown out of the crater—ejecta—in a surface explosion may be viewed in the same context as fragmentation since many accidental explosions occur on the ground where crater material provides a large volume of the thrown-out fragmented material. Data on ejecta are relatively scarce, but those available are particularly useful because they include observations of ejecta density distribution as functions of fragment size, explosion yield, ground material, and distance from explosion. Some of these measurements (reference 41) are given in Figures 2-42 and 2-43 for surface bursts of hemispherical 5-, 100-, and 500-ton TNT charges.

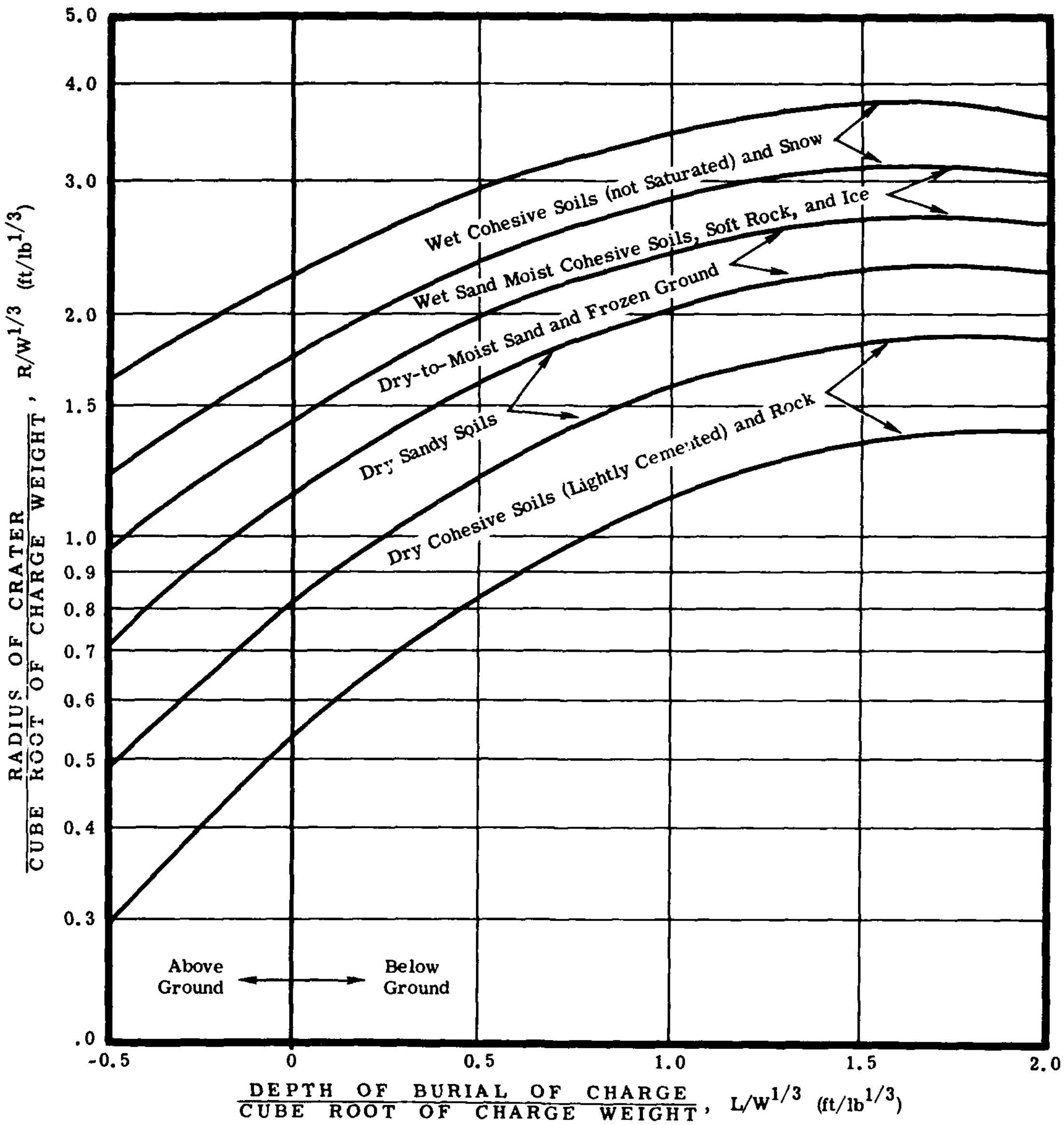


Figure 2-40 Apparent Crater Radius in Various Media

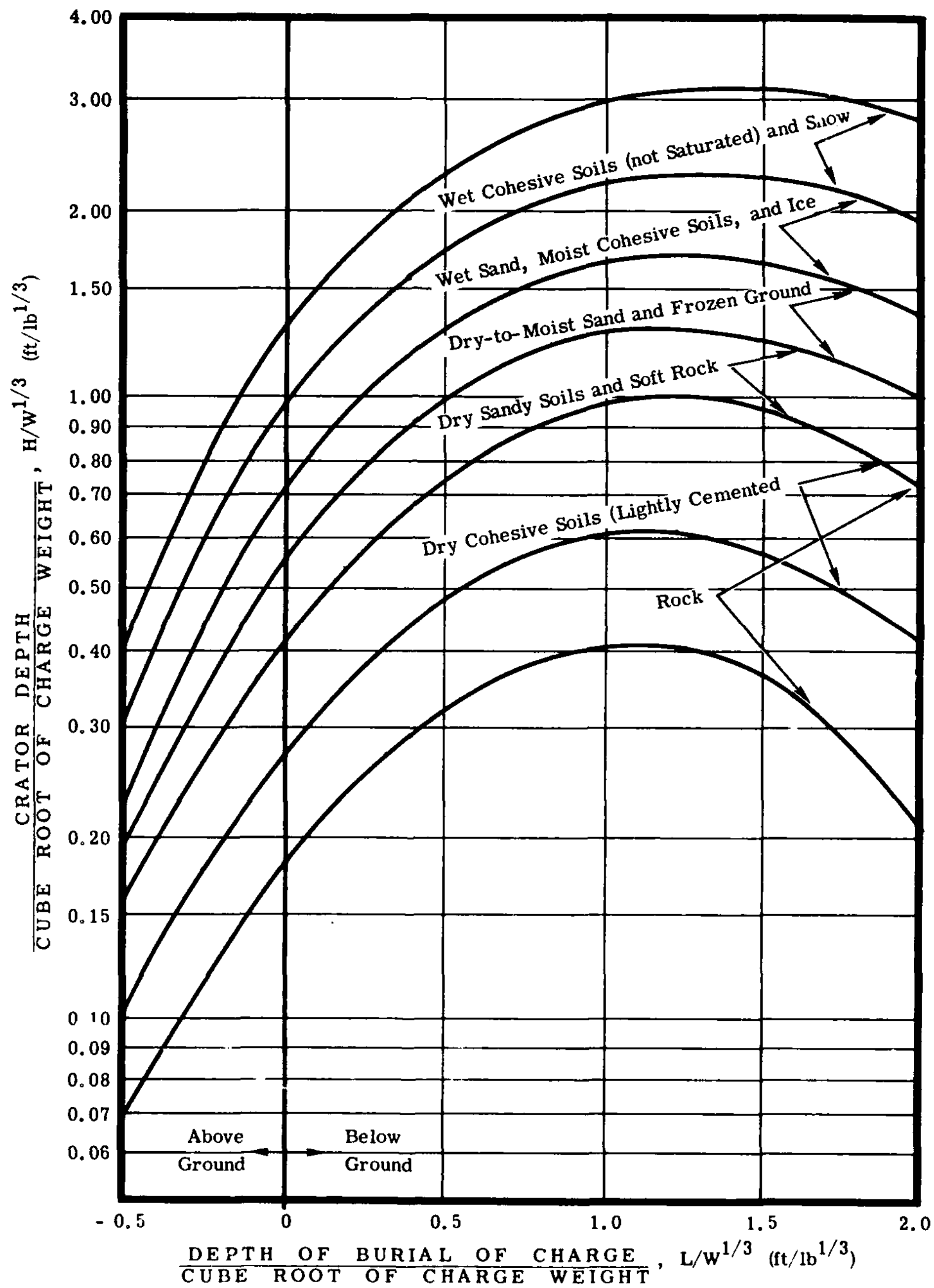


Figure 2-41 Apparent Crater Depth in Various Media

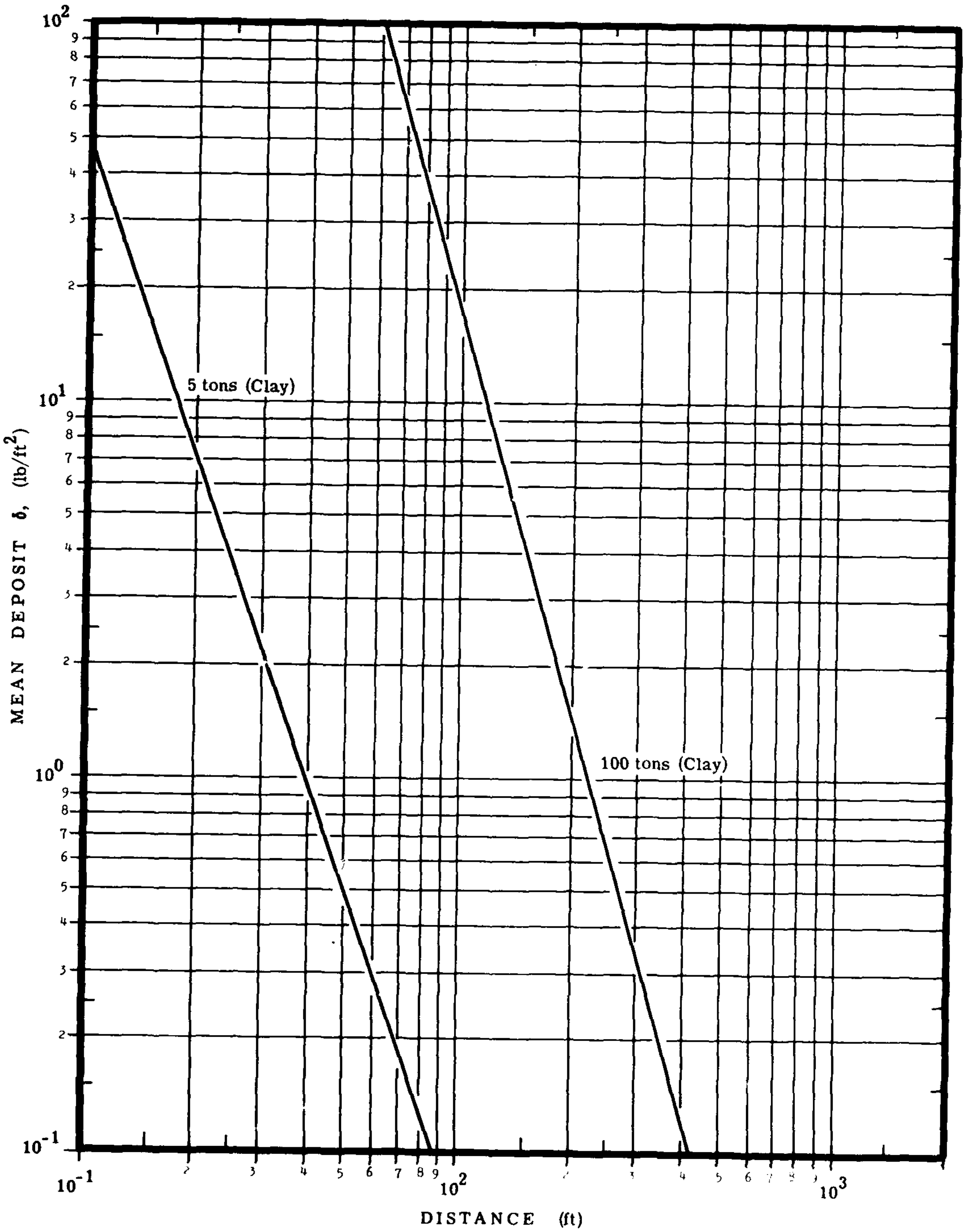


Figure 2-42 Ejecta Density versus Distance for 5- and 100-Ton Surface Bursts

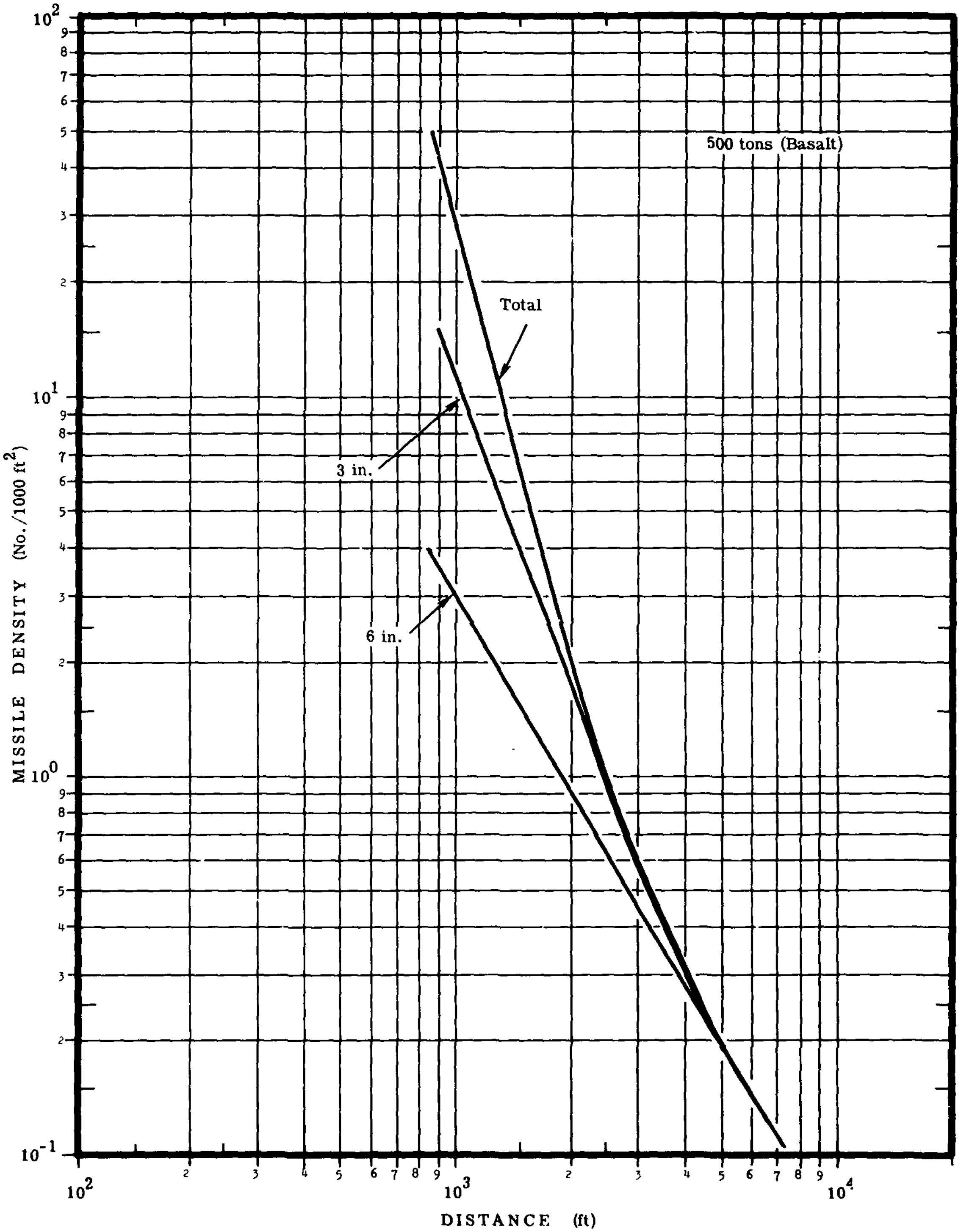


Figure 2-43 Missile Population Density versus Distance for a 500-Ton Surface Burst

Figure 2-42 presents the empirically derived curves of density of ejecta, i.e., the total weight of ground material deposited per unit of surface area, as a function of distance for 5- and 100-ton explosions over clay soils. For ground materials and weights of charge other than those given in the figure, the following functional relationship (reference 41) can be used to determine ejecta density, δ.

$$\delta = kr^{-n}W^{n-1} \qquad \text{Eq. 2-9}$$

The coefficient k in this equation is a constant related to the crater volume characteristics of the particular earth medium and the units used for δ, W, and r. W is weight of charge, and r is distance from charge. The value of n will vary depending on the charge weight; for charges up to 50 tons, use n = 2.93, for larger charges n = 3.65. The values of k for several earth media are tabulated below for δ in pounds per square foot, r in feet, and W in tons.

Constants Used in Ejecta Density Predictions
(Based on data of Reference 41)

Earth Material	k Up to 50 Tons	k 50 Tons and Up
Desert Alluvium	8.64×10^3	9.24×10^4
Basalt	1.77×10^3	1.89×10^4
Residual Clay	2.43×10^4	2.59×10^5
Clay (Unsaturated)	6.66×10^3	7.10×10^4
Clay (Saturated)	1.34×10^4	1.43×10^5
Limestone	2.60×10^3	2.77 x 104

The two curves in Figure 2-42 are representative of the two weight ranges discussed above. The curve labeled 5 Tons, (Clay) corresponds to n = 2.93 and k = 1.34×10^4. Likewise, the curve labeled 100 Tons, (Clay) corresponds to n = 3.65 and k = 1.43×10^5.

Figure 2-43 gives the empirically derived curve for missile population density, i.e., number of missiles per 1000 ft^2 of surface area, as a function of distance from a 500-ton explosion over basalt. Although a ready method of generalizing to other weights and other ground media is not available, this curve is included to complement Figure 2-32 which gives maximum fragment distance versus charge weight data. It can be surmised from these two figures that for a million pound explosion on the surface, fragments or ejecta may reach a distance of 10,000 ft with a population density of one fragment (missile) in somewhat less than 15,000 ft^2 at that distance.

2-8 DAMAGE TO STRUCTURES

Airblast from explosions provides an important damaging force to structures. Damage mechanisms and damage criteria are discussed in this section in terms of the basic physical parameters of air shockwaves presented in preceding sections. Curves of damage to (or response of) structures are given for a wide variety of types of structures, over a large range of charge weights, and for several levels of damage.

A generalized approach to the problem of structural loading also is given in order to indicate to the design engineer the transient hydrodynamic and aerodynamic considerations important to the loading problem. Explosions both internal and external to structures are discussed.

2-8.1 AIRBLAST LOADING. Before presenting data and information concerning the damage of specific structures from airblast loading, it is helpful to consider in some detail the interaction of airblast with a target in order to identify the important loading parameters. (The material that follows is a condensation of that presented in reference 4.) Take for example a plane airblast wave moving toward a simple, closed, box-like structure that faces the explosion. The instant before the wave strikes the structure, the following properties of the shockwave are known from figures presented in Section 2-4.

ΔP	Peak overpressure	ΔP_r	Reflected overpressure at instant of reflection
$\Delta P(t)$	Time variation of overpressure	$\tau+$	Duration of positive phase
Δq	Peak dynamic pressure	U	Shock velocity
q(t)	Time variation of dynamic pressure	u	Particle velocity

2-8.1.1 Diffraction Loading. When the blast wave strikes the forward face of the structure, the particle velocity immediately behind the shockfront is brought to zero, and the pressure at the shockfront jumps from the peak incident level ΔP to the reflected value ΔP_r. As the wave continues forward, the reflected pressure on the front face drops rapidly to the sum of the incident pressure ΔP and the dynamic (wind) pressure Δq. This sum is defined as the stagnation pressure ΔP_s. The wave diffracts around the structure and, if the wave is of sufficiently long duration, it eventually engulfs the structure with the incident pressure. It is seen that the maximum pressure differential between the front and back face of the structure exists at some time before the wave completely surrounds the building. Aside from forces that squeeze or crush the building, this pressure differential produces a lateral or translational force that tries to bodily move the structure in the same direction as the blast wave. This force is defined as the diffraction loading, and it is so named because it exists while the blast wave is being diffracted around the structure. In terms of damage, diffraction loading is normally indexed by the peak incident or reflected pressure and the time required for the shockwave to surround the building (length of building L/ shock velocity U). Large buildings having small window and door area and substantial loadbearing exterior walls such as reinforced concrete are typical examples of structures sensitive to diffraction loading.

2-8.1.2 Drag Loading. After the blast wave has completely engulfed the structure, the transient turbulences have diminished, the only pressure tending to bodily move the building is the dynamic pressure Δq acting on the structure. This dynamic pressure results from the wind (air particle motion) behind the shockfront. (These winds attain velocities of 160 miles per hour for 5-psi overpressure shockwaves.) Loading produced by the dynamic pressure is defined as drag loading. The magnitude of drag pressures are normally much lower than that of diffraction pressures (in the 50-psi-and-below range) but the duration of drag loading can be a large part of the positive duration of the blast wave. If the positive duration is considerably greater than the diffraction time, i.e., transit time of the shockfront across the structure or significant structural element, the drag forces provide a prime loading function on the structure. Such targets as bridges, smoke stacks, telephone poles, and buildings with large window areas, are usually considered to be drag targets for large charge explosions.

Although it is convenient in many instances to categorize structures as either diffraction or drag-type targets, and to consider the former to be primarily peak overpressure sensitive and the latter dynamic pressure and duration sensitive, the classifications are not hard and fixed. They are dependent on the airblast duration—structural characteristic length relationship. Any given structure, a wood-frame house for instance, may be a diffraction target for a 10-lb charge, but a drag target for a 100-ton charge. By the same reasoning, for many targets, equal attention must be given to both the drag and diffraction phases of exposure.

2-8.1.3 Detailed Loading Picture.

2-8.1.3.1 Diffraction Targets. Let us examine qualitatively the loads on the faces of several elementary structures. First, take the closed box-like building depicted in Figure 2-44, having length L, height H, and width B. Here, it is assumed that the walls are substantial and the door and window area is less than 5 percent of the total exterior surface area. When the blast wave first strikes the front face (t = O), the pressure acting is the reflected pressure ΔP_r. Experiments have shown that a good approximation of the time, t_s, for the pressure to fall to stagnation level ΔP_s is given by

$$t_s = 3S/U \qquad \text{Eq. 2-10}$$

where S is equal to H or B/2 whichever is less. Since the drag coefficient C_d for the front face is unity, the drag pressure (C_dq) is equal to the dynamic pressure Δq, and the stagnation pressure on the front face at time t_s is

$$\Delta P_s = \Delta P(t_s) + q(t_s). \qquad \text{Eq. 2-11}$$

Thereafter, the pressure decays with time so that, from t_s to t_+ the pressure at time t = $\Delta P(t) + q(t)$. The pressure time profile on the front face is given in Figure 2-45.

From an examination of the sides and top of the structure, it is seen that, although loading begins when the blast wave strikes the front face (t = O), the sides and top are not fully loaded until the wave has traveled the building length L, i.e., at time t = L/U. The average pressure ΔP_a at this time is the sum of the incident and the drag pressures at a mid-length distance L/2, so that

$$\Delta P_a = P(L/2U) + C_dq(L/2U). \qquad \text{Eq. 2-12}$$

From this point, the wave decays in the normal manner as shown in Figure 2-46.

The shockwave arrives at the back face at t = L/U, but it requires an additional time 4S/U for the pressure to become uniform at a level

$$\Delta P_b = P(4S/U) + C_dq(4S/U). \qquad \text{Eq. 2-13}$$

Figure 2-47 shows the subsequent pressure loading on the back face. Note that the drag coefficient, C_d, is a function of the magnitude of the dynamic pressure. Values of C_d for ranges of dynamic pressure are tabulated below.

Dynamic pressure q	C_d (side, top, and back)
0 - 25 psi	-0.4
25 - 50 psi	-0.3
50 - 130 psi	-0.2

If the structure is partially open, i.e., 30 percent window and door area, and if there are no substantial partitions to restrict the flow of the blast wave inside the building, it is seen that the interior of the structure will be subjected to the incident pressure. Thus, to determine the net loadings on the building walls, accounting of the internal pressure must be made. Superimposed on the three previous external pressure-time curves are shown in Figures 2-48, 2-49, and 2-50. The differences between the two curves for a particular face represents the net loading on the wall. Both the partially open and closed structures in the above discussions are considered diffraction structures because they primarily respond to the peak pressure loads occurring in the diffraction time $0 < t < (L + 4S)/U$.

2-8.1.3.2 Drag Targets. Let us now consider an open-frame structure where small separate elements are exposed to a blast wave. Truss bridges are regarded as typical examples of open-frame structures, as are steel-frame office buildings with a majority of glass wall area. Industrial buildings with light steel, aluminum, or asbestos wall panels become open-frame structures after the initial impact of the blast wave removes the glass and siding. It is assumed that diffraction loading is not significant in these cases because of the extremely short diffraction time compared to the positive duration of the wave. Thus, the predominate loading mechanism is the drag pressure C_dq.

For a single frame member such as an "I", channel or angle beam, the C_d is about 1.5, therefore,

$$\text{force on single member} = C_dq(t)\,A_i \qquad \text{Eq. 2-14}$$

where A_i is the member area projected perpendicular to the direction of the blast wave. For the force on the total frame

$$\text{force on total frame} = C_dq(t)\,\Sigma A_i \qquad \text{Eq. 2-15}$$

but, since some members of the frame structure are shielded by others, the effective drag coefficient C_d is

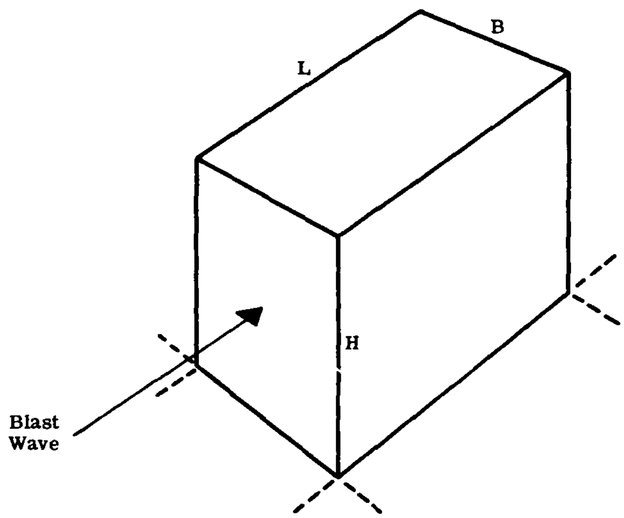


Figure 2-44 Representation of Closed Box-like Structure

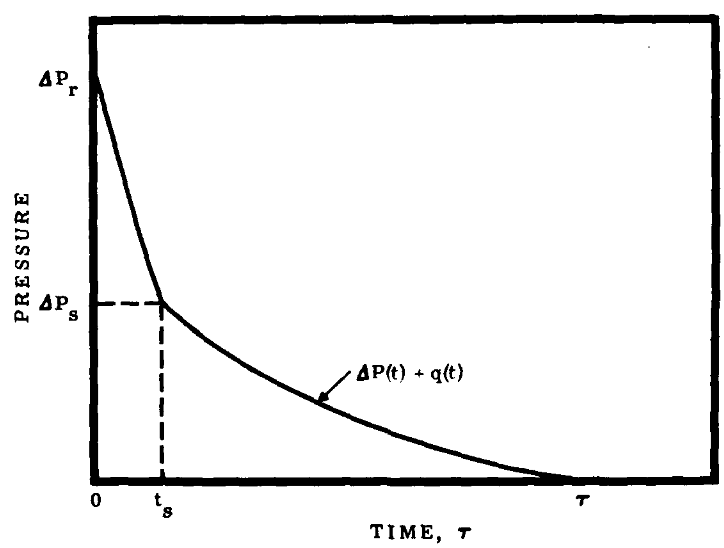


Figure 2-45 Average Front Face Loading of Closed Box-like Structure

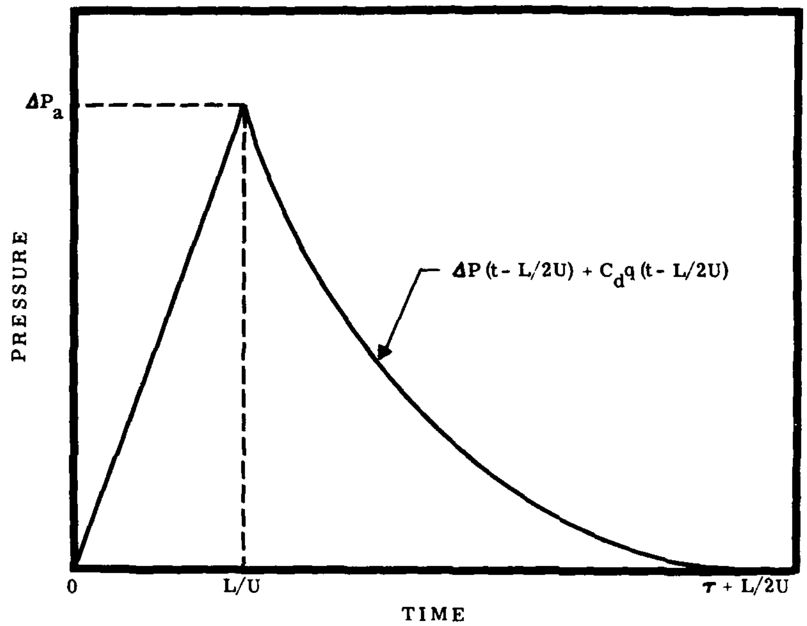


Figure 2-46 Average Side and Top Loading of Closed Box-like Structure

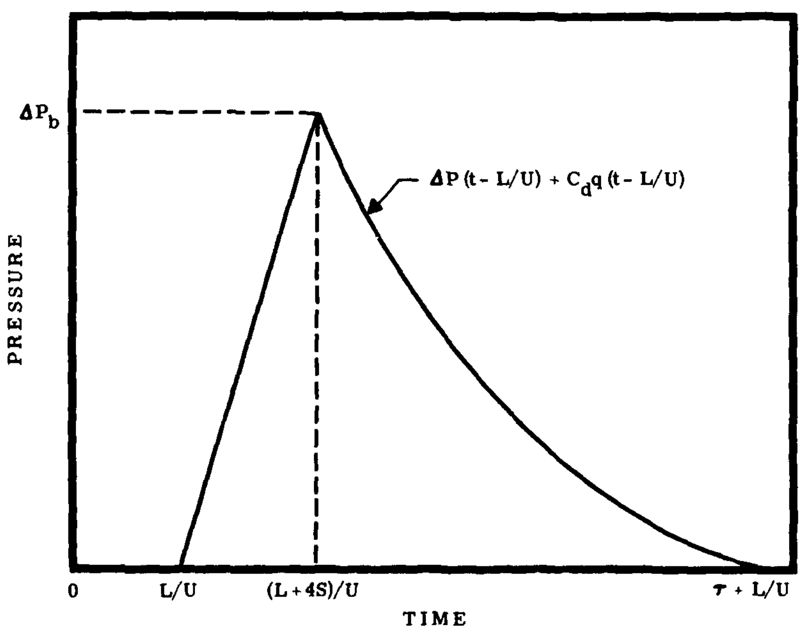


Figure 2-47 Average Back Face Loading of Closed Box-like Structure

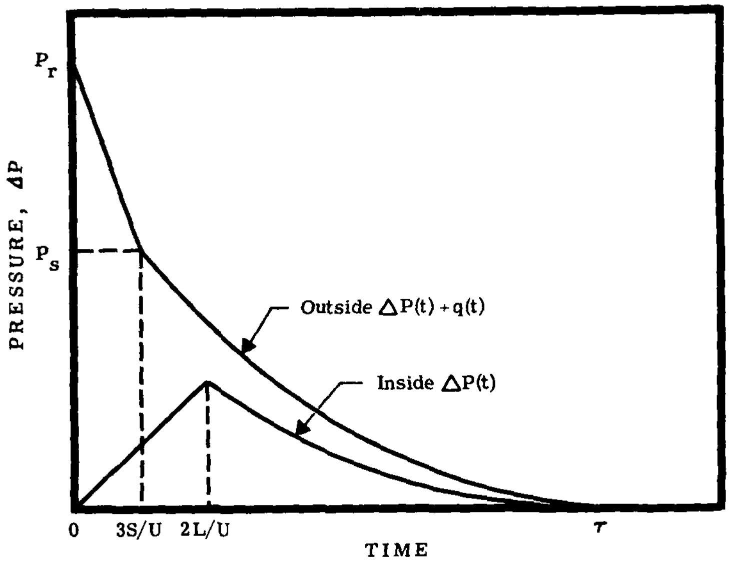


Figure 2-48 Average Front Face Loading of Partially Open Box-like Structure

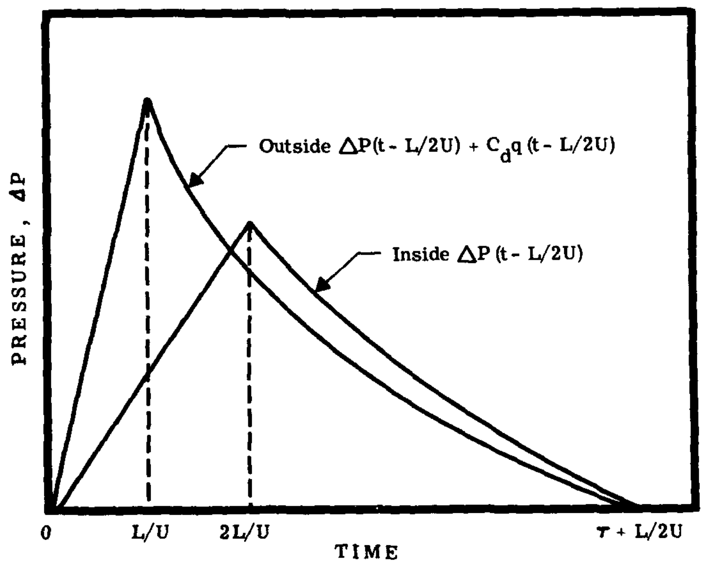


Figure 2-49 Average Side and Top Loading of Partially Open Box-like Structure

reduced to 1.0, and

force on total frame = $q(t)\,\Sigma A_i$. Eq. 2-16

Let us now examine cylindrical structures such as telephone poles, smoke stacks, and arched structures like quonset huts. In the latter case the analysis is more difficult because the angle of attack changes as the wave propagates around or over the structure. The treatment given here is applicable to semi-circular structures subjected to incident pressures below 25 psi. These results can be applied to fully cylindrical structures since they consist of two semi-cylinders with the same loading on each half. Consider a wave moving toward a building as shown in Figure 2-51, for which a loading at point z is desired. Figure 2-52 gives the loading at this point. The dependence of the pressures and times and the drag coefficient defined in Figure 2-52, on the angle α is given in Figure 2-53, where ΔP_r is the ideal reflected pressure from a normal flat surface.

2-8.2 RESPONSE OF STRUCTURES TO BLAST. The specific degree of damage incurred by a specific structure exposed to any particular blast wave can be calculated laboriously in terms of the various parameters of the problem, e.g., loading functions as presented in Section 2-8.1 and response characteristics of materials and structures. However, for many situations of interest, a more practicable solution is at hand. A large body of empirical and analytical information has been accumulated which permits generalizations. This section presents such practical, generalized data.

Many different types of structures are considered, and to aid identification, the structures are listed by usual function, e.g., guided missile plant assembly building, and by structural features, e.g., single story, light steel frame. Several degrees of damage are considered and defined. Criteria for the degrees of damage are given in terms of charge weight, peak overpressure, and dynamic pressure as appropriate. Information is also presented in this section on damage to some miscellaneous but important targets such as glass, personnel, silos, and launching pads.

2-8.2.1 Degree of Damage Definitions.

a. Severe Structural Damage (SSD): At least that degree of structural damage which precludes further use of a structure for the purpose for which it is intended without essentially complete reconstruction; requires extensive repair before usable for any purpose.

b. Moderate Structural Damage (MSD): At least that degree of structural damage to principal load-carrying members (trusses, columns, beams, and load-bearing walls) that precludes effective use of a structure for its intended purpose unless major repairs are made.

2-8.2.2 Types of Structures. This listing identifies structures by principal structural (architectural) features.

a. General Types

SS - Single story
MS - Multistory
I - Igloo

b. Load-Bearing Material

WF - Wood frame
WB - Masonry load-bearing walls
VLSF - Very light steel framed
LSF - Light steel framed
SF - Steel framed
VLRC - Very light reinforced concrete
LRC - Light reinforced concrete
RC - Reinforced concrete

c. Other Features

EQR - Earthquake resistant
BR - Blast resistant
TC - Ton capacity cranes
CS - Corrugated steel siding

The above type designations may be used in combinations to more fully describe building structures. For instance:

MS/SF-EQR - Multistory steel framed building of earthquake resistant design

and

SS/RC(60–100 TC) - Single story reinforced concrete building with 60–100 ton capacity cranes.

2-8.2.3 Classification of Structures. The following tabulation classifies structures in terms of usual operational functions taking place in the structure. The buildings are described also as to structural type. The tabulation lists the appropriate figures from which to obtain damage criteria.

	Type	Figure
a. Heavy Munitions (torpedoes, large shells, etc.)		
Foundry, force, and machine shop buildings	SS/LSF	2-56
b. Light Munitions (small arms ammunitions, etc.)		
Machine shop and assembly buildings	SS/LSF	2-56
	SS/LRC	2-56
	MS/RC	2-56
c. Guided Missile Plants		
Assembly buildings	SS/LSF	2-56
	SS/LRC	2-56
d. ICBM Plants		
Production buildings	SS/LSF	2-56

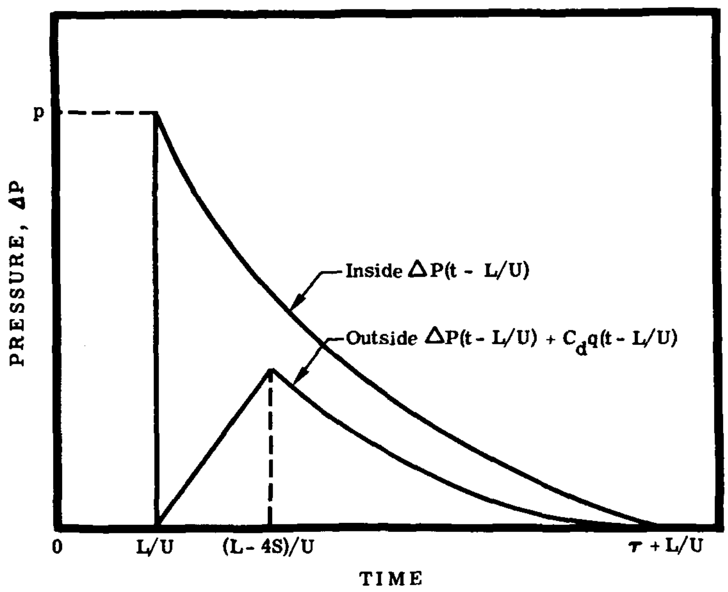


Figure 2-50 Average Back Face Loading of Partially Open Box-like Structure

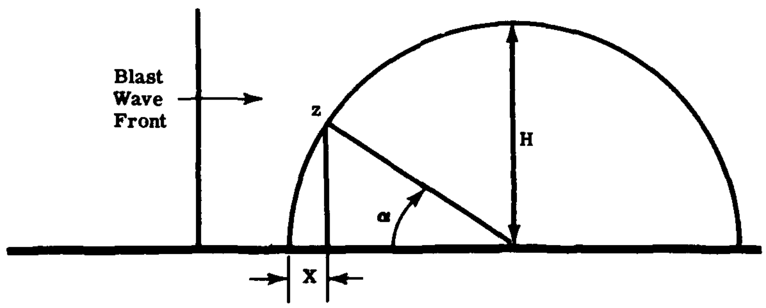


Figure 2-51 Representation of a Typical Semicircular Arched Structure

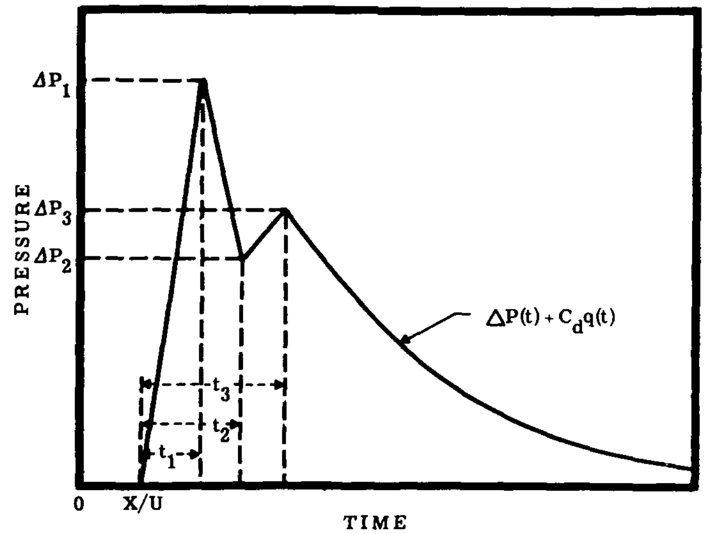


Figure 2-52 Typical Pressure Variation at a Point on an Arched Structure Subjected to a Moving Blast Wave

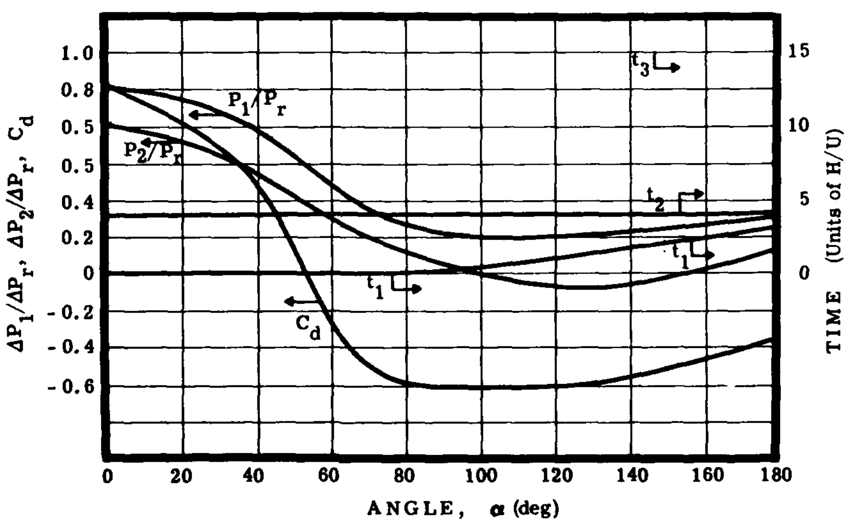


Figure 2-53 Variation of Pressure Ratios, Drag Coefficient, and Time Intervals for an Arched Structure

	Type	Figure
e. Explosives		
Preparation, loading, finishing, and assembly buildings	SS/WF	2-54
	SS/VLSF	2-55
	SS/VLRC	2-55
f. Ammunition Depots		
Above-ground buildings	SS/WF	2-54
	SS/WB	2-54
	SS/VLSF	2-55
	SS/VLRC	2-55
g. Propellants and Commercial Dynamite		
Manufacturing buildings	SS/WF	2-54
	SS/VLSF	2-55
	SS/VLRC	2-55
h. Reinforced Concrete Igloos (arch-shaped, 27 feet wide and 2 feet of earth cover)	RCI	2-54
SSD - Arch collapsed, moderate to severe damage to contents		
MSD - Door and end wall blown in, light to severe damage to contents		
i. Corrugated Steel Igloos (arch-shaped, 12 feet wide with 2 feet of earth cover)	CSI	2-54
SSD - Arch collapsed, moderate to severe damage to contents		
MSD - Door and end ball blown in, light to severe damage to contents		

2-8.2.4 Damage to Structures. Damage to the structural types and classifications considered earlier are presented in Figures 2-54 through 2-58. The data are presented in the form of iso-damage curves for severe and moderate damage as functions of charge weight and peak overpressure or dynamic pressure, as appropriate. (The figures are based on nuclear weapon data adjusted for TNT equivalence.)

2-8.2.5 Damage from Small Explosions. Where the explosion yield is relatively small and the positive duration of the blast wave small compared to the transit time of a complete structure or even a structural element, localized damage can occur to some part of the building. Figure 2-59 gives data on the damage to reinforced concrete walls from explosions. For open-framed structures where localized damage may exist, the curves in Figure 2-60 for steel columns, and Figure 2-61 on concrete columns serve as ready damage criteria.

Much useful empirical data on the response of concrete walls in three-sided, roofless storage structures for quantities of high explosives in the range from 100 to several 1000 lbs is available in reference 42. Also, a detailed engineering analysis of the local response of concrete to high explosive attack for various spacing conditions is presented in reference 43.

2-8.2.6 Damage to Miscellaneous Targets.

2-8.2.6.1 Glass Windows. Glass windows are extremely frangible targets with the normal range of window types all shattering at pressure levels of 0.5 psi. Although much study has been made of window damage as functions of glass type, size, and mounting, and blast characteristics, the lower average pressure level at which any window will break is hard to predict. Variations in glass properties and pane-mounting stresses probably account for much of the unpredictability.

2-8.2.6.2 Damage to Reinforced Concrete Wall Panels. Table 2-11 gives maximum distance at which an air-backed reinforced concrete wall or wall panel will experience various degrees of damage due to explosions of TNT in air.

These data derive from tests, both model and full scale, on rectangular panels with face dimensions from 3 to 25 times the thickness. Charges used in tests ranged from about 1-1/4 oz. to 1700 lb. Test panels were supported along all four edges, and results showed no appreciable difference between freely supported and fixed edges.

Tests involved various degrees of reinforcing and different explosives, but all data were reduced to a basis of 1/4% steel by volume and TNT-filled bombs. Degree of damage and ratio of central deflection to span correlate fairly well for slight, moderate, and heavy damage.

Tabulated data refer to about 1/4% reinforcing steel by volume. For 1/2% steel, multiply thickness values by 0.9 (graph only of Fig. 2-59) for breaching and by 0.7 for other degrees of damage (graphical and tabular values).

Table 2-11
Damage to Reinforced Concrete Wall Panels

Description of Damage	Type of Damage	Average Deflection/ Span, in./ft
Slight	Slight Cracking and Bending	0.1
Moderate	Light Punching and Cracking with Possibly Some Spalling	0.5
Heavy	Heavy Punching, Shattering, or Possible Perforation	1.2
Breaching	Perforation with Extensive Scabing. Bars May be Bent or Bulged	---

Figure 2-55 Damage to Selected Targets as Function of Dynamic Overpressure and Explosion Yield (Medium Light Construction)

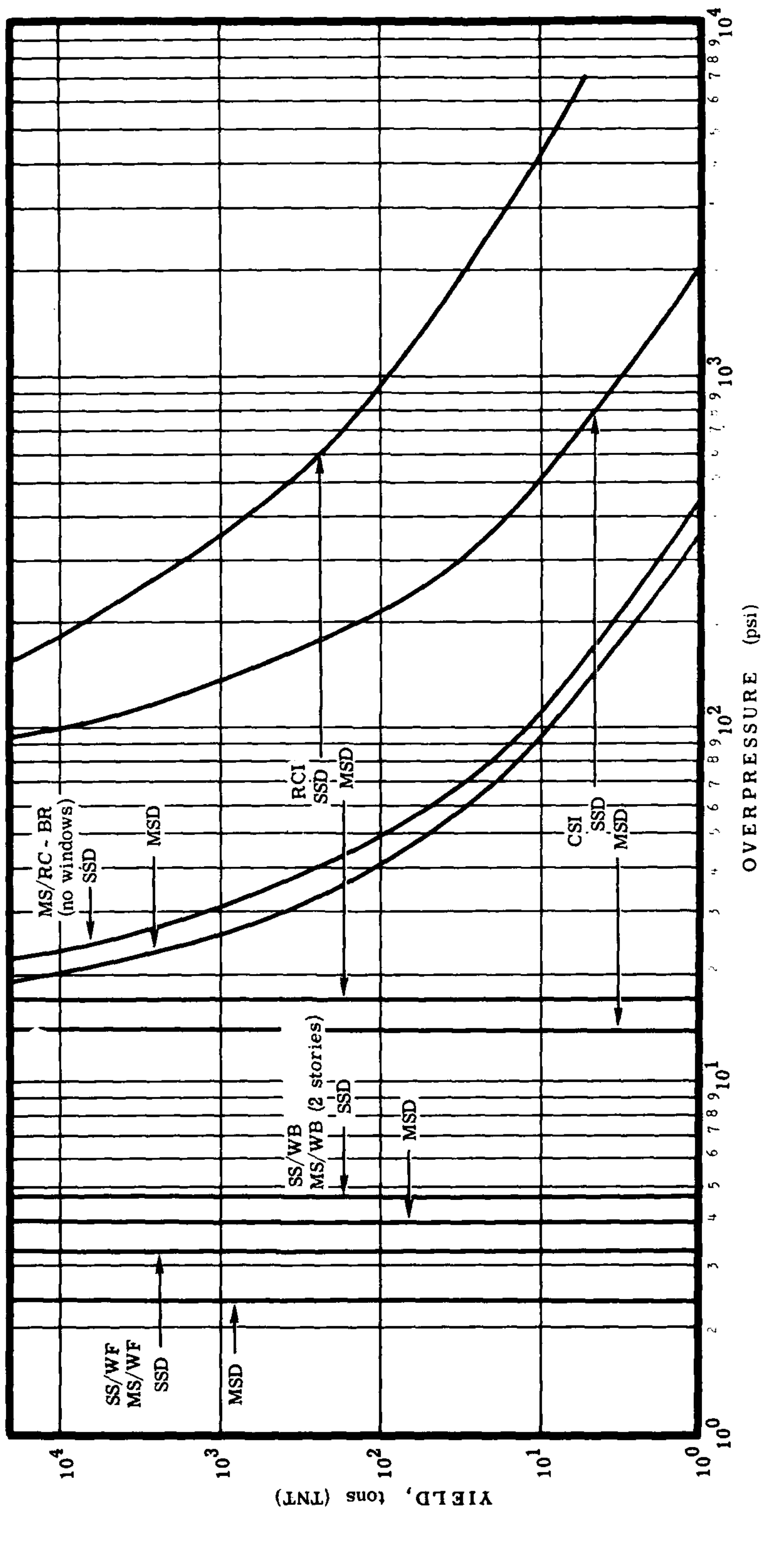
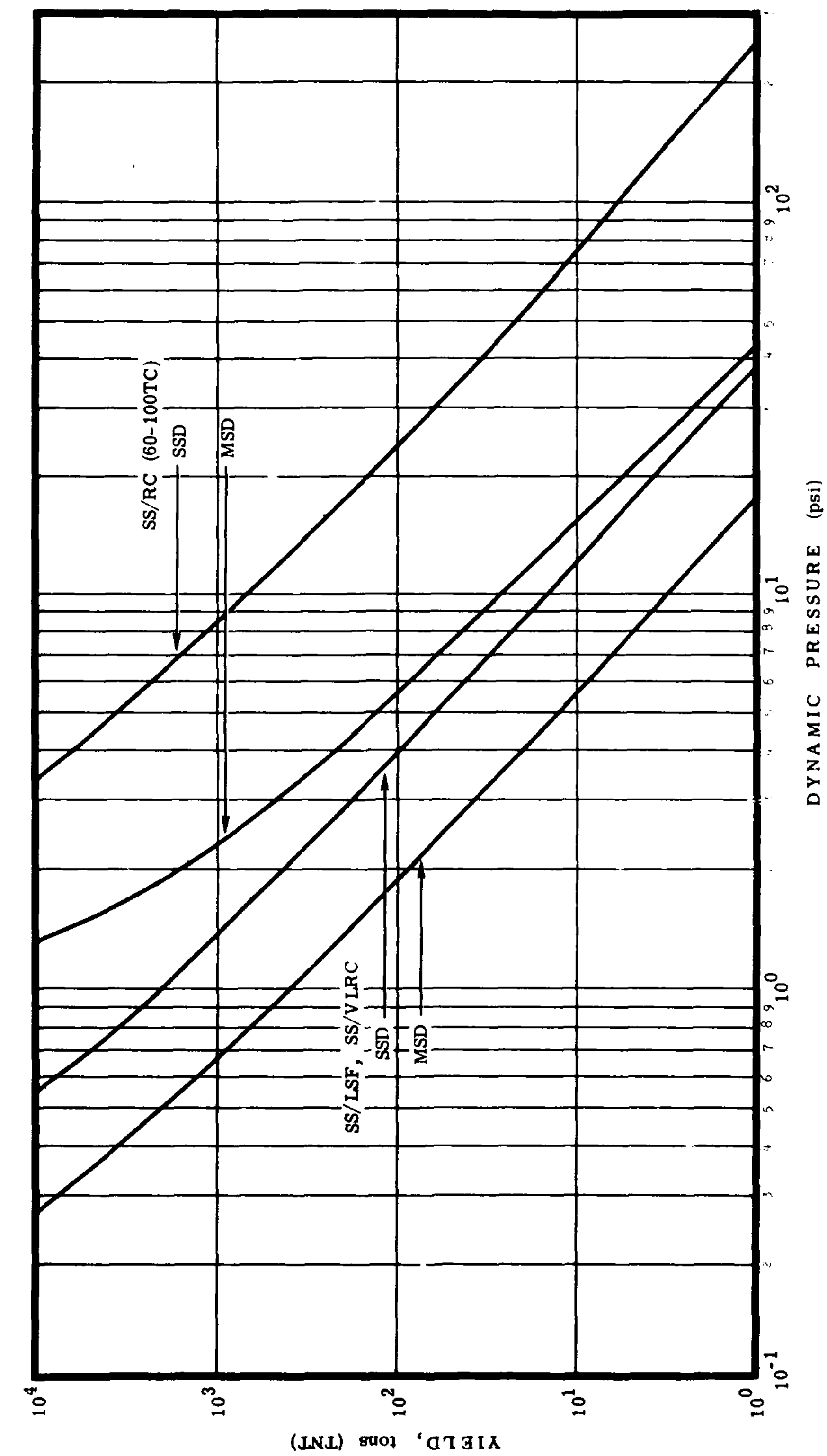


Figure 2-54 Damage to Selected Targets as Function of Dynamic Overpressure and Explosion Yield (Light Construction)


SS/RC (60-100TC)
SSD
MSD
SS/LSF, SS/VLRC
SSD
MSD
DYNAMIC PRESSURE (psi)
YIELD, tons (TNT)
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

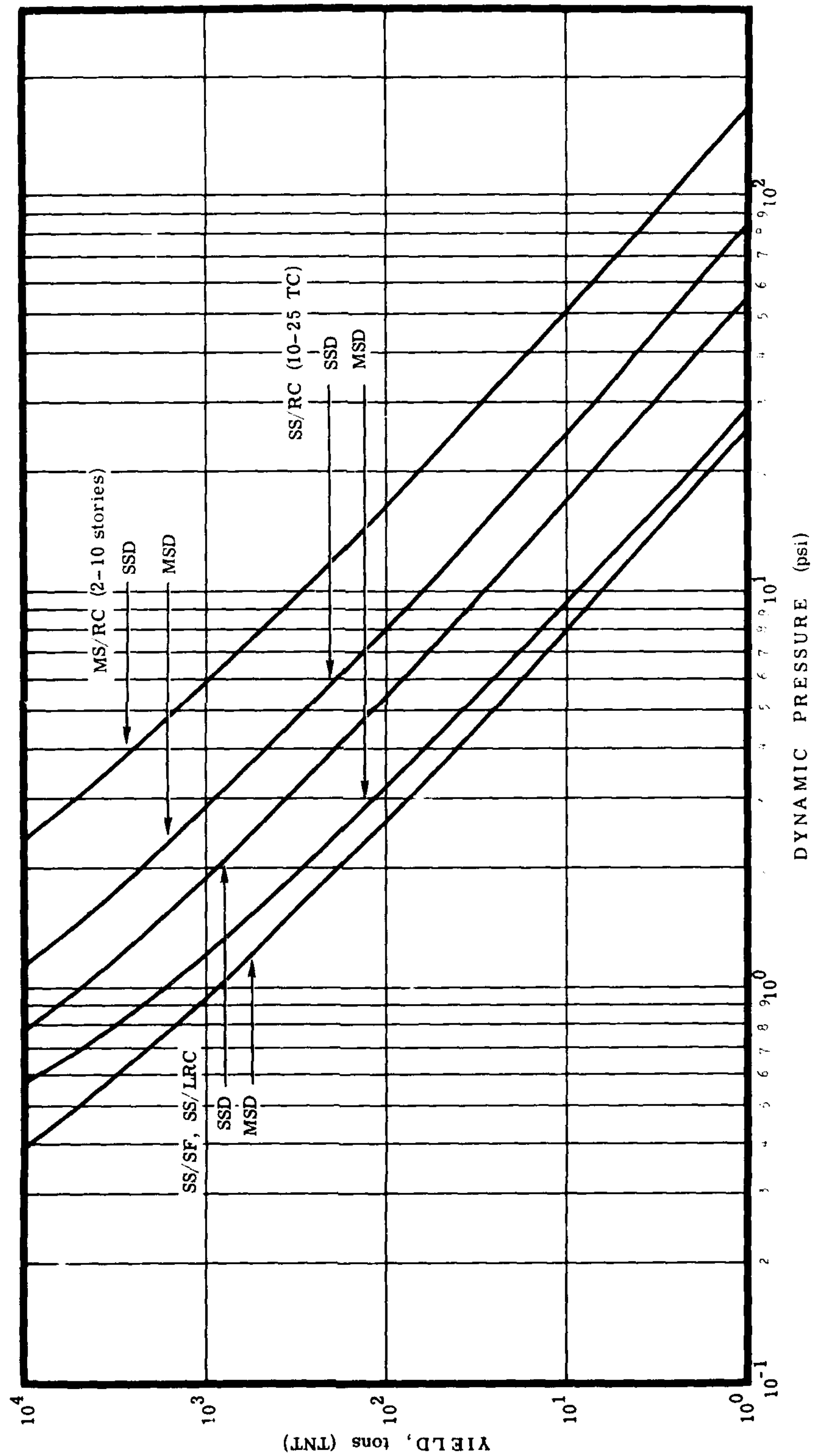


Figure 2-56 Damage to Selected Targets as Function of Dynamic Overpressure and Explosion Yield (Medium Construction)

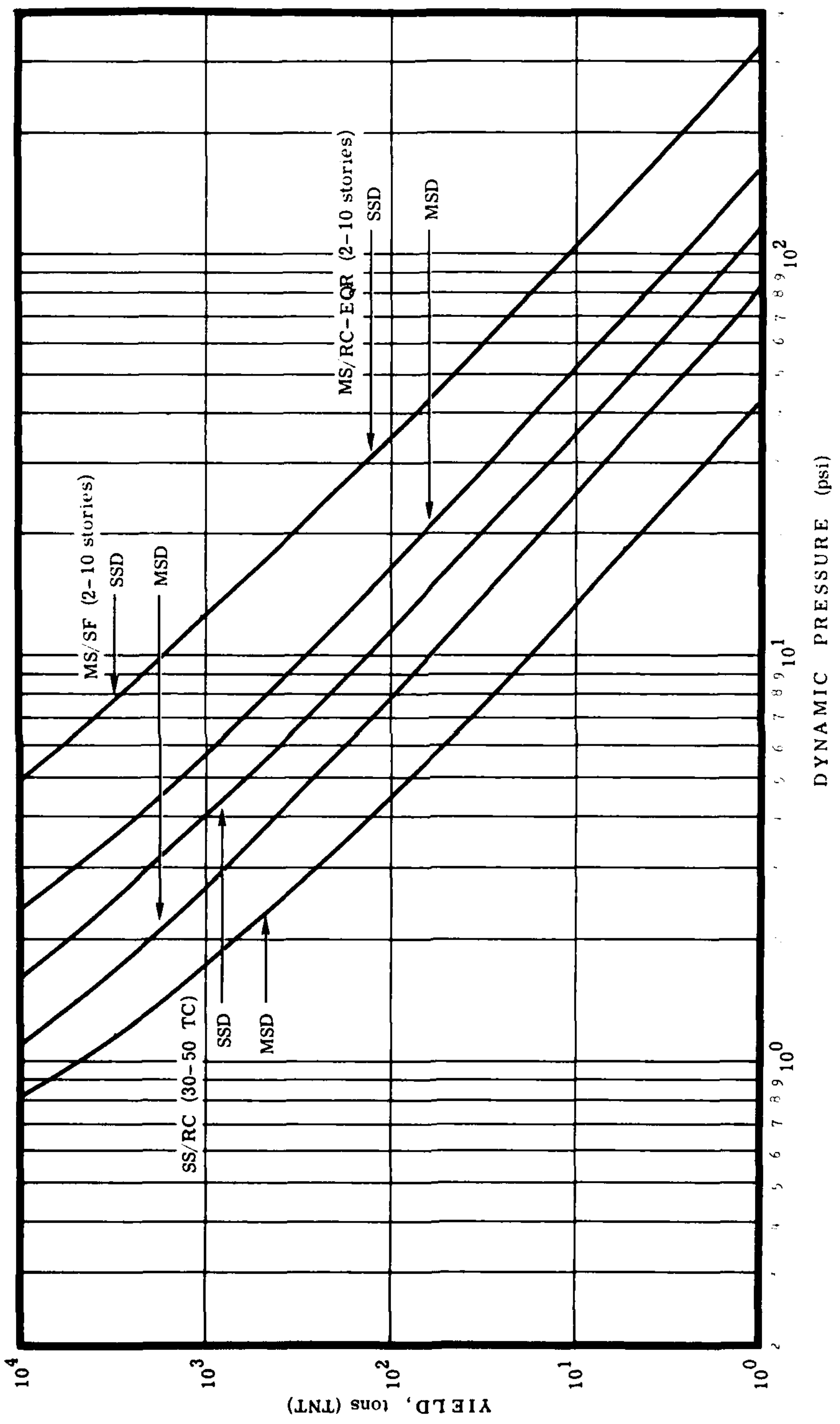


Figure 2-57 Damage to Selected Targets as Function of Dynamic Overpressure and Explosion Yield (Medium Heavy Construction)

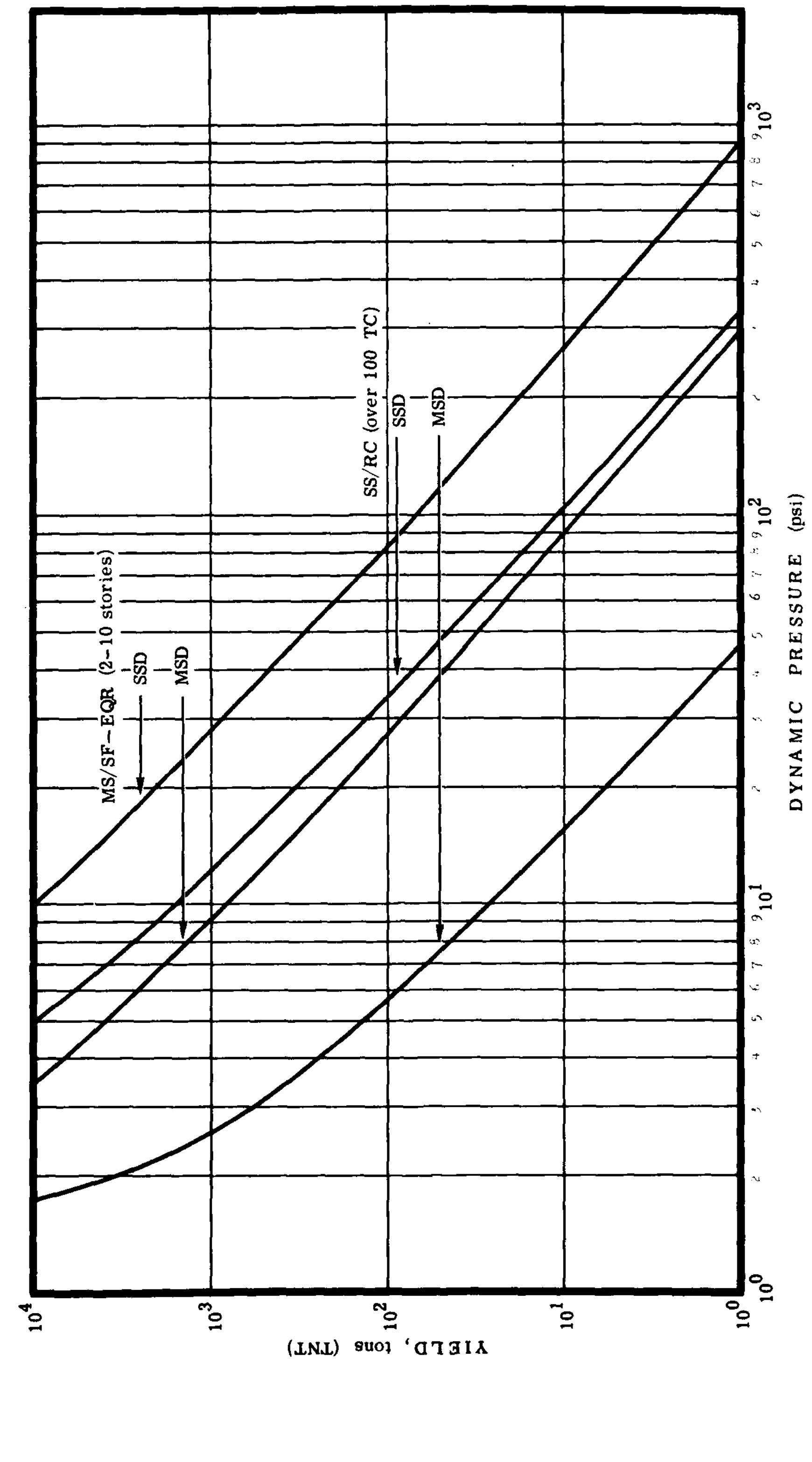


Figure 2-58 Damage to Selected Targets as Function of Dynamic Overpressure and Explosion Yield (Heavy Construction)

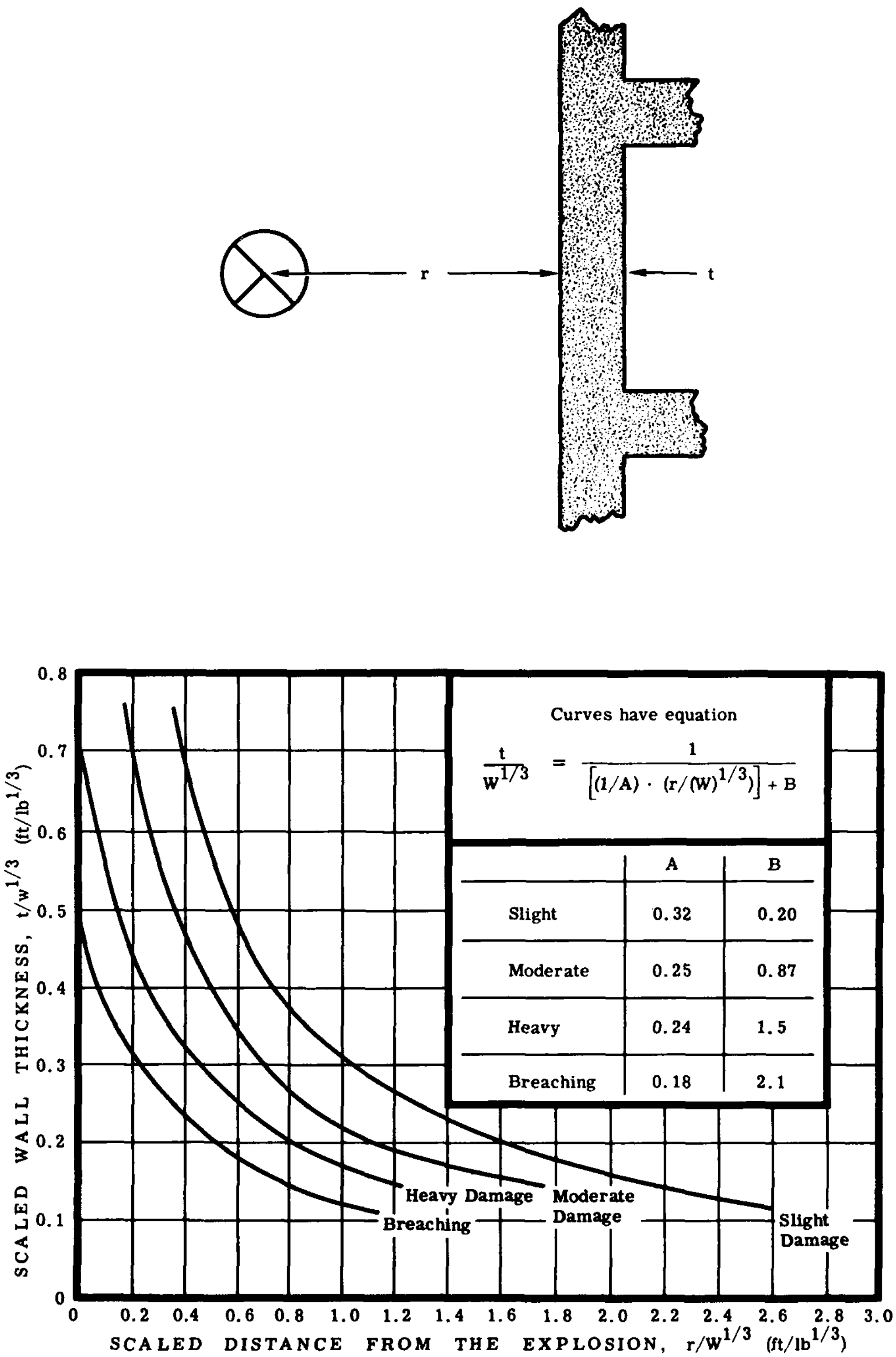


Figure 2-59 Damage to Reinforced Concrete Wall Panels from TNT Explosions in Air

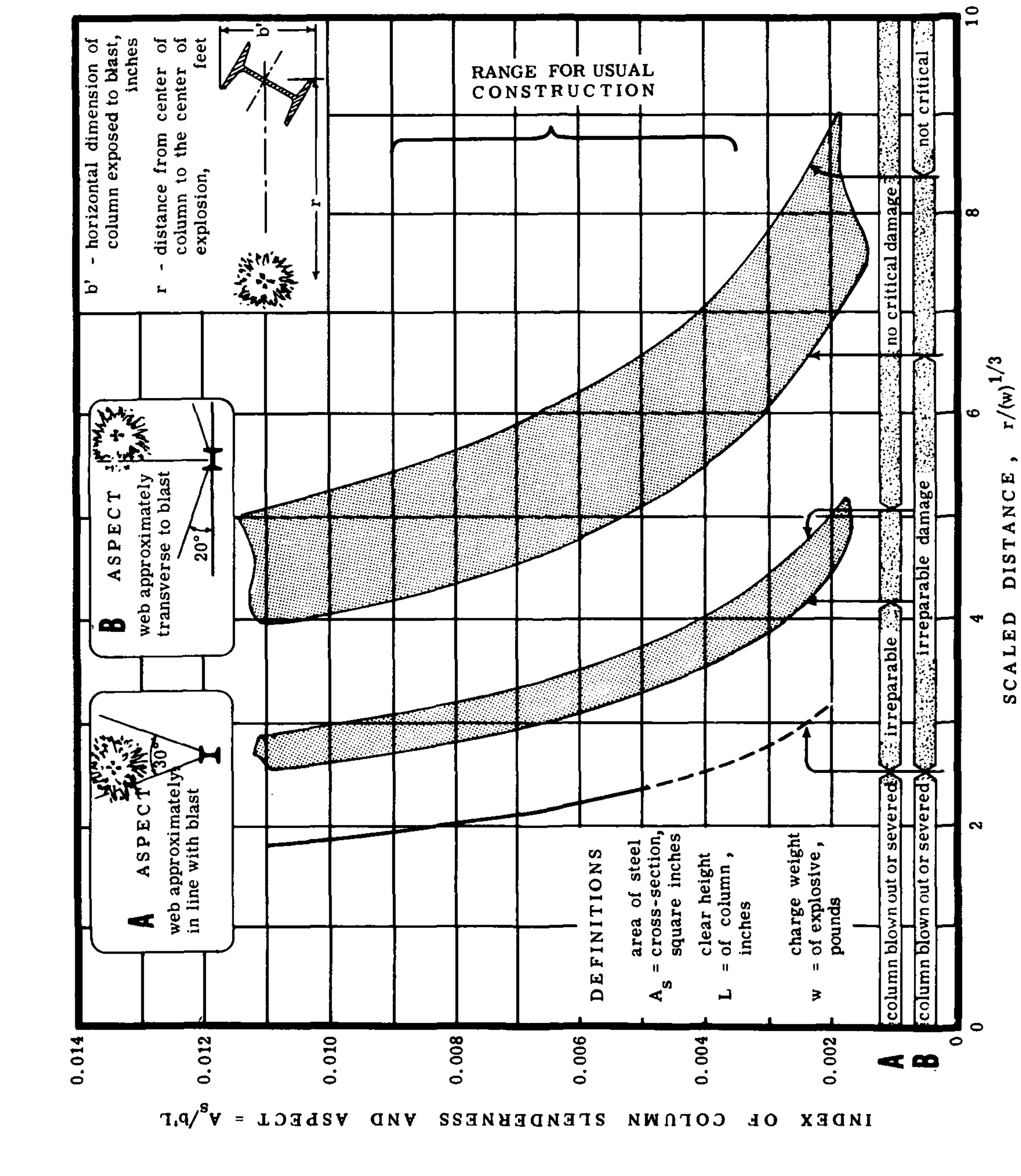


Figure 2-60 Blast Damage to Steel Columns

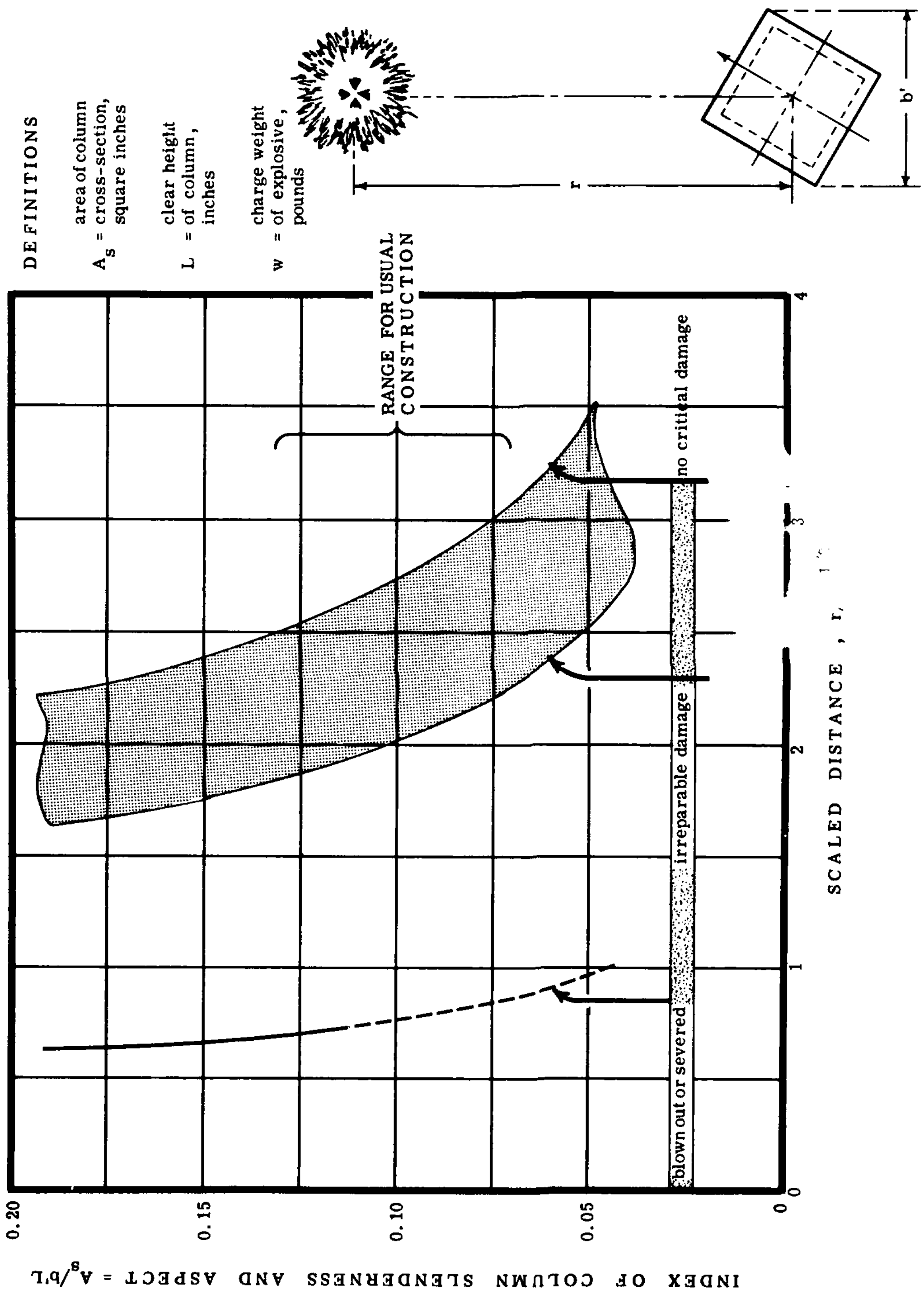


Figure 2-61 Blast Damage to Reinforced Concrete Columns

Figure 2-59 gives damage curves in terms of scale variables $r/w^{1/3}$ and $t/w^{1/3}$ where t = wall thickness (ft), r = distance from wall to explosion and w = weight of charge (lb).

Laboratory tests have shown that at least 10 millibars (0.15 psi) are required to break windows (reference 44) and yet, large explosion yields and sonic booms have produced window breakage at distant sites at the 2 millibar (0.03 psi) level.

Another factor must be considered in making window breaking predictions: at the low level of pressure of interest, i.e., from 0.5 psi down, atmospheric variations in temperature and wind velocity may produce channeling of the blast wave. This will result in focusing of the blast energy at large distances from the explosion with intervening skip or shadow zones. For best predictions, therefore, the detailed atmospheric structure must be known.

2-8.2.6.3 Silos. If there is a large explosion in a silo, obviously that silo will be severely damaged or destroyed. Whether this explosion will damage or destroy nearby silos depends on the size of the crater formed, the extent of the rupture and plastic zones, and the ground shock. The extent of these parameters can be estimated from Section 2-7. Note that the data in Section 2-7 are for explosions buried underground. An explosion within a silo is somewhat different since the explosion takes place in an air space below the ground surface (i.e., the explosion is decoupled from the surrounding earth). This decoupling should reduce the explosive effects in the earth by some factor. For this reason, the information in Section 2-7 gives upper limit values for this silo problem.

There is very little information available on the damage ranges to silos from external surface or underground bursts. However, it can be surmised that the ground shock would have to be very intense to cause severe damage to a silo. At distances beyond the rupture or plastic zones, a silo should not receive any serious damage. However, it is noted that although the silo may not receive serious damage, the internal equipment may be severely damaged.

2-8.2.6.4 Launch Pads. The extent of damage to launch pads may be determined from Section 2-7. Although crater dimensions for explosions on or above a launch pad are not given, the dimensions may be estimated by assuming that a launch pad is similar to a hard rock surface.

2-8.3 INTERNAL LOADING AND RESPONSE OF STRUCTURES. In the following discussion, it is assumed that the explosion is confined within a structure and the weight of explosion gases is small compared to the weight of enclosed air. A confined explosion produces two mechanisms that can cause damage to the structure. First, there is the usual shock wave; however, following the shock is an equilibrium pressure established in the enclosure. This static pressure is generated from the transfer of energy from the gaseous explosion fireball to the enclosed air. In many cases, walls that may not be damaged by the short duration shockwave may be damaged due to this sustained gas pressure. Data on the incident and reflected peak overpressures for the shock and the static gas pressure have been presented in Sections 2-4.3 and 2-4.6; additional information on reflected impulse and duration is given in the following Figures 2-62 and 2-63.

The design criteria for structures to contain an internal explosion are functions of many parameters, e.g., configuration, elastic and plastic properties of structure material, and mass of structure. Here several basic containment structures are discussed qualitatively, and particular design features are examined. First, let us look at spherical and cylindrical structures where the explosion occurs at or near the centroid of the building. Since these types of structures are made normally of steel or aluminum, the discussion will be limited to metals. The transient shock loading response can be analyzed by writing the equation of motion for the spherical or cylindrical structure as follows (reference 45):

$$2h\sigma + \rho h R\,(d^2U/dt^2) = R\,p(t)\ .\ .\ .\ \text{sphere} \qquad \text{Eq. 2-17}$$

$$\rho R^2 h_o\,(d^2\epsilon/dt^2) + \sigma h = R_o\,(1+\epsilon)\,p(t)\ .\ .\ .\ \text{cylinder} \qquad \text{Eq. 2-18}$$

where the nomenclature is:

- h instantaneous wall thickness
- h_o initial wall thickness
- R instantaneous radius
- R_o initial radius
- ρ mass density of wall material
- σ true stress
- U radial velocity of wall
- ϵ radial strain
- p pressure
- t time

The pressure-time history of the shock can be approximated by

$$p(t) = P(1 - t/T) \qquad \text{Eq. 2-19}$$

where:

- P is peak reflected pressure
- T is duration of reflected pressure

From the elastic and plastic properties of the material, these equations can be manipulated to analyze the response of the particular structures. Usually, shock loading is the predominate damaging mechanism in these types of structures since metals are strong in tension, but the hoop stresses should be checked with the static gas pressure to ensure no additional vessel damage.

In rectangular wall construction, which is usually reinforced concrete, the analytical treatments become difficult. Normally, the best procedure is to examine the damage resulting from the shockwave on the basis of the external explosion data presented for reinforced concrete walls in Figure 2-59. Also, references 42 and 43 provide additional information on concrete wall response for various special cases. If the wall does

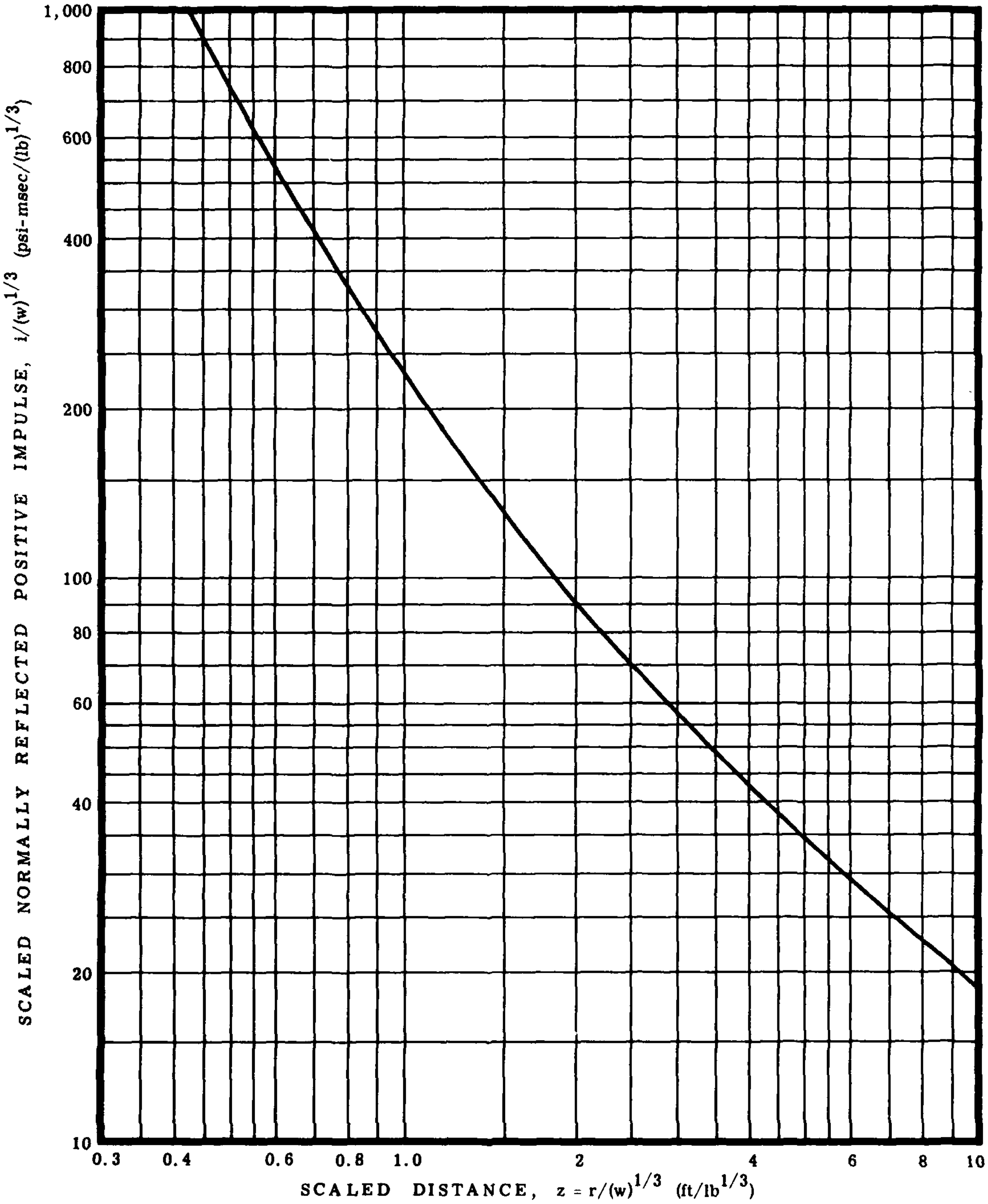


Figure 2-62 Scaled Normally Reflected Positive Impulse versus Scaled Distance for Pentolite

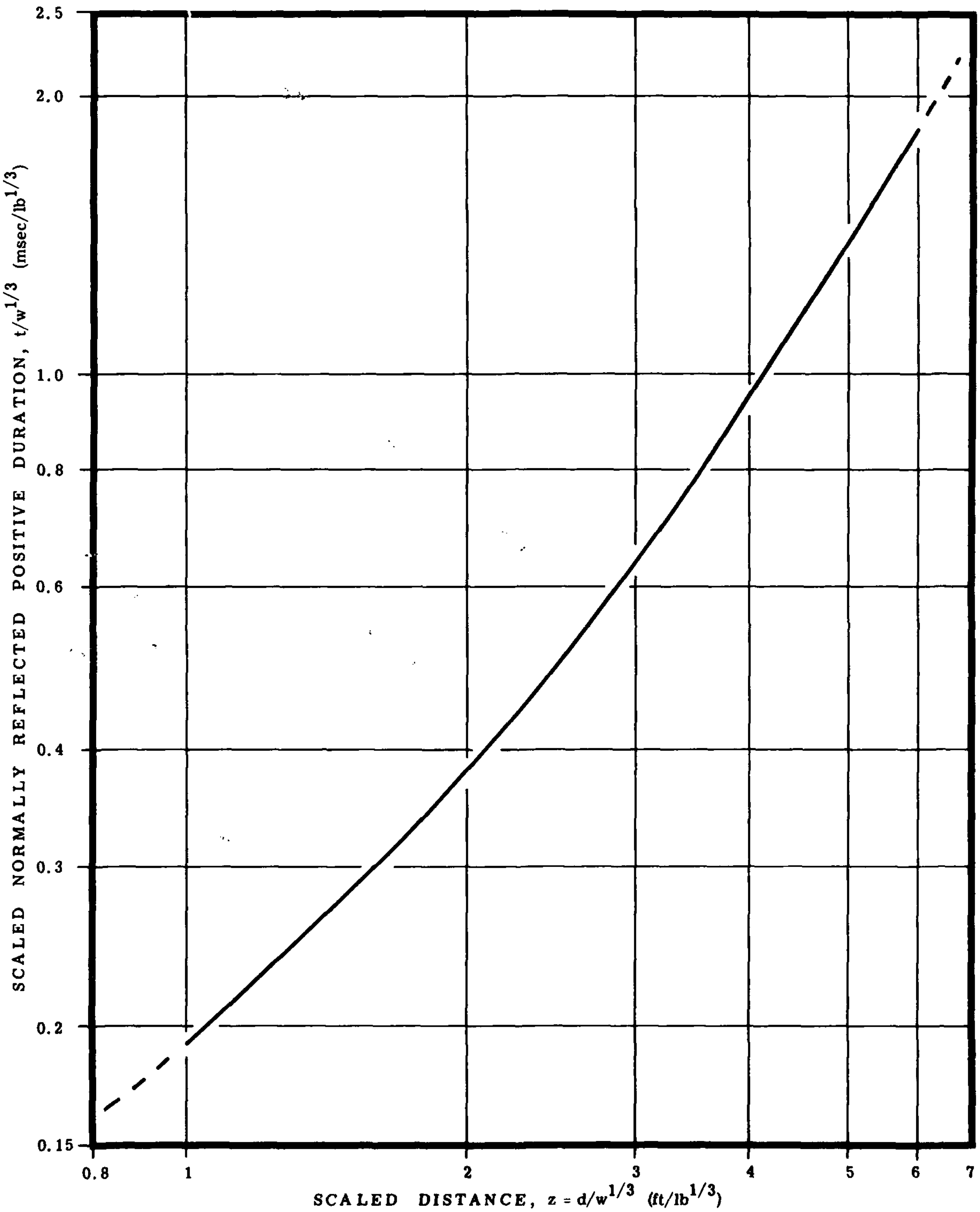


Figure 2-63 Scaled Normally Reflected Positive Duration versus Scaled Distance for Pentolite

not fail from the shockwave, its structural integrity should be tested with the static gas pressure by treating the walls as simply supported, uniformly loaded, flexural plates. (In many cases, specific buildings that are especially designed to withstand the shock load are susceptible to the gas loading and must be equipped with adequate venting to relieve the static overpressure. On the other hand, such structures as explosion test "bombproofs" may be constructed as essentially closed structures in order to preclude costly and intricate labyrinths for outside noise abatement.)

Underground containment structures such as earth-covered arched construction can be analyzed in a manner similar to cylindrical structures. The mass of earth surrounding the structure presents a significant inertial resistance to the motion of the load-bearing walls. In terms of the equation given for cylinders, the mass of the earth should be appropriately accounted for in the inertia force portion of the equation. If the elastic response of the structure is important, then the pre-compressive stresses due to the static earth load should be taken into account in formulating the stress function σ.

2-9 FACILITY PLANNING AND SITING—STRUCTURAL CONSIDERATIONS

The damaging effects of explosions can be reduced or eliminated by a number of methods. Targets can be placed outside the effective damage range of explosions. *Targets can be hardened to withstand relatively high* levels of blast, and the effects of an explosion can be confined to some small, prescribed region. The utilization and degree of any of these methods or combination of methods usually is tempered by practical considerations. To name a few: the cost of hardening or confining, the real estate available for dispersing targets around a possible explosion source, the compatibility of the basic design and function of the target structure with hardening and dispersal, and the esthetic compatibility of hardening residential-type structures.

The basic blast data and loading information contained in the earlier sections of this chapter are intended primarily for use in estimating the response or damage of various targets in a number of explosion situations. The data also are applicable to designing and siting structures; but, of course, the data are only part of the input to these problems. (See references 46 and 47 for detailed design procedures and reference 48 for siting requirements, i. e., quantity-distance tables that are currently in use.) The airblast data are applied to these new problems in much the same way as they are used for predicting response; hence, no further general discussions of this topic will be made.

Special attention is given to considerations of containers designed to confine explosions. And, a discussion of the airblast effectiveness of barricades as protective construction is presented.

2-9.1 BARRICADES.

A barricade is a constructional feature used to provide for safety in the design of explosives facilities. It is a natural or artificial terrain feature partially or totally surrounding a building, and is considered to reduce the effects of an accidental explosion on other buildings. Some protection is considered to be provided by a natural or man-made hill, by another structure, or sometimes by trees. In practice, a barricade is more precisely defined, at least in military manuals for the construction of explosives facilities, as a massive wall or mound of certain dimensions and materials. In general, these manuals provide for safety at explosives facilities by requiring specific spacings of other structures and facilities from a given quantity of explosives. The manuals require distances to be approximately doubled when neither the source nor the target building is barricaded (references 48, 49, 50, and 51).

Although barricades are in widespread use, systematic correlation of barricade design with explosion effects is not a feature of such usage. In fact, the barricade as a problem involving blast effects, aerodynamic loading, and structural response to dynamic loads is not a part of the literature on barricade usage. This is due to some extent to the fact that adequate and systematic explosion effects information was not available until World War II, long after barricade usage was well established. However, in the past two decades, little has changed in the area of barricade usage.

As a result, the basis has never been developed for rational engineering design of barricades as structures subject to blast loads and affecting the blast loads on other nearby structures. Even more important, under*lying questions regarding the effectiveness of barri*cades in providing protection from specific explosion effects remain unanswered. The intuitive considerations on which barricade usage are based directly contradict, in many respects, today's well established technical information.

Blast effects data do not support the idea, for example, that a barricade located near an explosion will reduce damage to buildings in the far field by reducing the shock pressure levels. This is because, unlike fragments thrown from an explosion, the blast is not stopped by an obstacle. Instead, it diffracts or bends around the obstacle and, except for minor energy losses, is reconstituted in essentially full strength at a distance beyond the obstacle of about five obstacle widths. Yet, the American Table of Distances (reference 48) as presently constituted implies that shock pressures in the far field are reduced from free surface levels by more than 50 percent (depending on distance from the source) because of the presence of a barricade near the source.

Another example is the case of a building and an adjacent barricade that is engulfed by a blast wave that originates from the explosion some distance away. The barricade is at best of dubious (and in any case undetermined) value as a blast shield, again because of blast diffraction. In the same manner, as in the previous example, rules governing present usage credit such a barricade with substantial improvement in safety as a result of an implied major reduction of pressure.

The above interpretation of effects information as it bears on barricade usage is supported by several collective studies of the damage to buildings in the vicinity of accidental explosions. A recent and comprehensive study of this type (reference 11) analyzed nearly all available and pertinent data. No evidence was found that barricades affected the average distance at which various categories of damage occurred.

At short distances from an explosion, propagation of detonation to a second explosive site is a predominant concern. Catastrophic damage to nearby structures is generally not avoidable and therefore, the primary concern is to prevent initiation of explosives at nearby sites. This is a complex problem involving blast, fragments, and fire from the source explosion, as well as type of ordnance material, sensitivity of the explosive, and type of structure at the target.

Primary fragments (those originally in direct contact with the explosive material) traveling at very high velocity are of major concern. On the other hand, in many cases, secondary fragments (those resulting from blast and impact from moving debris) are the chief concern (reference 42). In this regard, the high degree of damage to, and debris resulting from, barricades themselves (reference 11) raises serious reservations about the universal effectiveness of barricades even for the purpose of stopping fragments.

A definitive basis for dealing with this problem obviously is not now available. However, several useful studies have been made recently (references 52, 53), and additional efforts are underway and planned by the Armed Services Explosive Safety Board (ASESB) as part of a comprehensive effort to evaluate to what extent, if any, barricades are an effective aspect of protective construction.

2-9.2 CONTAINMENT VESSELS. In the following discussion, a containment vessel is defined as a substantial metal container that is capable of withstanding a large internal explosion in a small enclosed space. Such a vessel could be used for safe storage of explosives subject to accidental detonation, or it could be used as a test chamber in which explosion experiments could be conducted safely. In the first type of use, the vessel could be permanently deformed and damaged beyond repair but yet serve its function of containing the accidental explosion. In the latter use, the vessel is normally expected to withstand repeated internal explosions below some specified limit without permanent damage.

The optimum configuration for a vessel to contain a centrally located internal explosion is a spherical vessel. Here the entire vessel wall can be loaded uniformly which, in turn, utilizes the full biaxial tensile strength of the wall material. However, spherical vessels are often expensive to construct; thus, less costly cylindrical vessels are generally used. Some of the beneficial uniform loading features found in the spherical shape are also present in cylinders. But from simple hoop-stress considerations, the circumferential stress levels in a cylinder are twice those of a sphere for the same loading pressure. The poorest vessel configuration is that of a rectangular-shaped vessel, but in some instances, the simplicity and cost of construction make it attractive. Normally, failure in this type of vessel is localized at the center of a wall panel or at the corner joint where severe bending stresses can be developed. Therefore, a large portion of the stress and, more important, the strain energy absorption potential of the vessel material is unused.

If the specifications for a containment vessel, irrespective of configuration, permit only elastic response, then the safest design criterion is to treat the peak reflected shock pressure as a static load and limit all stresses in the vessel to the material yield strength or less. In the event that this ultra-conservative approach cannot be used or leads to an impossible design situation, a transient analysis such as presented in Section 2-8.3 can be employed.

For cases where it is acceptable for the vessel to undergo plastic deformation and the full containment potential of the vessel can be utilized, the most important blast parameter becomes the reflected impulse. This follows from the fact that the plastic response time of the vessel is generally large compared to the duration of the reflected shockwave. The transient analyses given in Section 2-8.3 can be used to estimate the containable explosion for centrally-loaded spherical vessels. They can also be used for centrally-loaded cylinders, but since this configuration is more widely used, there exists experimental information and data that make it unnecessary to assume the usual conservative plastic and dynamic properties of materials required by the transient analyses. Picatinny Arsenal (reference 54) empirically determined the curves shown in Figure 2-64 for aluminum and 304 stainless steel cylinders with various diameters and wall thicknesses. Caution should be exercised in extrapolating these curves beyond their given ranges primarily because of the entirely empirical basis of the curves, and also because of known non-scaling parameters. Also, a safety factor of at least two should be applied to the charge weight to account for variations in material strengths and welding procedures. More definitive data have been developed by the Naval Ordnance Laboratory (NOL) for water-filled cylinders where a wider range of materials and vessel sizes were investigated (reference 55). The following theoretical/empirical equation (2-20) was developed to express the safe containable charge weight W in terms of vessel size and conventional material properties.

$$W = \left[\frac{0.1536 \epsilon_u w^{0.85} (3.41 + 0.117 R_i/h_o)(R_e^2 - R_i^2)^{1.85}}{10^5 (2\sigma_y + \sigma_u + \sigma_u \epsilon_u)^{-1} (1.47 + 0.0373 R_i/h_o)^{0.15} R_i^{0.15}} \right]^{0.811} \qquad \text{Eq. 2-20}$$

where the nomenclature and units are:

- W charge weight (pentolite), lb
- w weight density of vessel material, lb/ft^3
- R_i initial internal radius of vessel, ft
- R_e initial external radius of vessel, ft
- h_o initial wall thickness of vessel, ft
- ϵ_u conventional ultimate strain of vessel material, in./in.
- σ_y conventional yield stress of vessel material, psi
- σ_u conventional ultimate stress of vessel material, psi

Equation 2-20 is applicable to water-fill cylinders with length/radius ratio greater than or equal to 4, and it is considered safe in light of end constraints, welding, and material variations. NOL also found that for empty cylindrical vessels (containing only air at atmospheric pressure) the safe weight or explosive that may be contained is at least twice that for a water-filled vessel.

Rectangular containment vessels are rarely used to contain an explosion where the mechanism of gross plastic deformation is desirable. This is due to the localized nature of failure in rectangular vessels and the inability of this type of construction to utilize the full potential of the structural material. For this reason, the complexity of a three-dimensional dynamic and plastic stress problem, no general information or data is available to establish definitive design criteria for rectangular containment vessels.

All of the previous discussions have been limited to centrally located explosions. However, in many cases, the expected explosion can occur at points other than the centroid of the vessel. Here again, no general information is known to exist to form general design criteria. The problem of vessel deformation can be bounded by assuming the vessel to be loaded symmetrically and uniformly with the greatest impulse existing at any particular local area. It is reasonable to expect the resultant deformation to be less severe than that actually occurring from an eccentrically located explosion. However, an additional problem arises due to the unbalanced loading, and this is the acceleration of the vessel as a body in the direction of the unbalanced load. Here Newton's law of motion for rigid bodies should suffice to estimate the translational motion of the vessel.

2-9.3 BLASTING MATS. Blasting mats are heavy mats woven of large diameter hemp rope or of steel wire rope and chains that are placed in the vicinity of an explosion to catch flying material and debris produced by the blast. One to 1-1/2-inch hemp rope and 1/4- to 1/2-inch steel wire rope are the most common materials used in mat construction. Such mats are widely used in road and earth moving construction to prevent underground explosions from producing potentially dangerous flying earth and rocks. Steel wire rope mats have also been used to catch metal fragments resulting from metal cased explosions such as experimental test vessel failures. In all cases, these mats are effective in reducing flying debris, but it should be noted that any mitigating effect on the air shock that the mats might produce is secondary to their intended purpose. Concerning design criteria for selecting the type and material for a mat, there appears to be none–other than the experience of the user and the manufacturer.

2-9.4 FRANGIBLE CONSTRUCTION CONCEPTS. Attention is currently being devoted to evaluation of frangible construction concepts for the design of explosives/propellant operating and storage facilities. Such concepts appear to be promising for applications to large quantities of liquid/solid propellants or similar materials where the bulk is such that conventional "hardened" construction techniques, i.e., reinforced concrete, require such wall thicknesses as to become economically and structurally infeasible. Under these conditions, as noted previously, fragments produced by the failure of the "hardened" structure may create a greater problem, in terms of lethality and facility damage, than the primary fragments produced by the failure of the explosives material, space vehicles missile, etc., housed within the confining structure.

While the term, "frangible construction" as presently used, has not been clearly defined, a good definition would appear to be the one outlined in NASA Defense Purchase Request CC16115 and as outlined in the paper, "Ballistic Investigations of Protective Structures for Space Vehicles, etc.," reference 56, as follows: "A structure which will remain intact long enough to provide some attenuation of the most far ranging fragments, but which will not contribute secondary fragments beyond the range of the attenuated primary fragments and will not provide sufficient confinement to increase the blast potential of the explosion." This concept appears to have much promise. One type of material considered promising is lightweight aluminum "honeycomb" panels which weigh approximately 3 lbs/sq ft and have very desirable thermal properties. Other materials such as plastics, lightweight wood and lightweight steel backed by sand, as in the steel arch magazines, are variants of this approach.

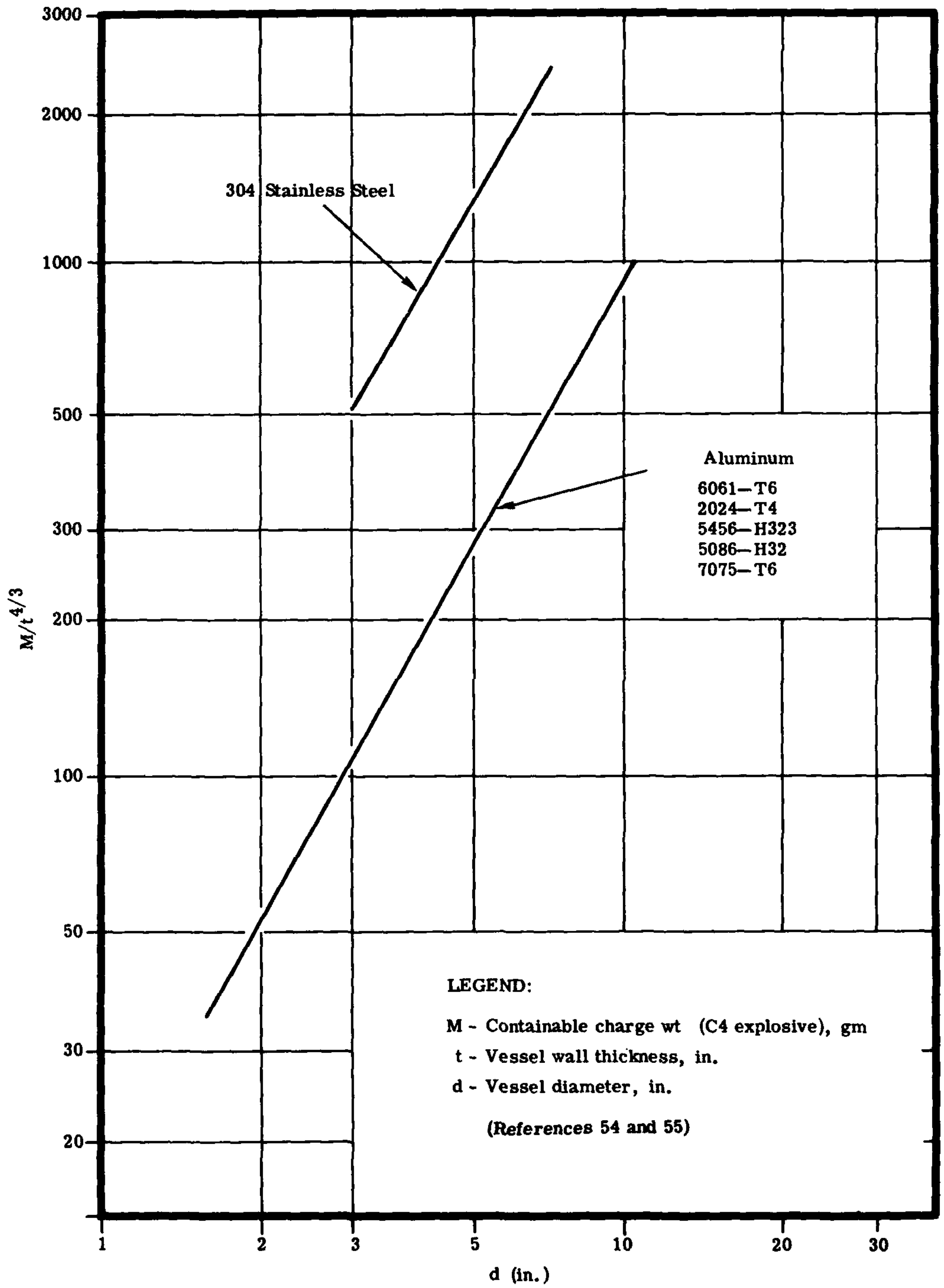


Figure 2-64 Containable Charge Weight for Cylindrical Vessels

2-10 RESPONSES OF PERSONNEL TO BLAST WAVES

2-10.1 BLAST (SHOCK WAVE) ENVIRONMENTS. Explosions generate air propagated blast (shock) waves that, depending on their energy content, may produce varied damaging effects on men exposed to them. These effects may be the consequence of direct exposure to the blast wave or they may result from indirect causes, such as the impact of high velocity solid materials on the man's body or the transport of the exposed man through the air terminated by a violent impact with the ground or other solid object in the environment. These hazards, potential for physical damage to the human body, range from no effect, through probable minor cuts, bruises, and scratches to severe lacerations and broken bones. At higher blast energy levels rupture of the eardrums results and on exposure to still higher energy levels, severe lung damage, allied damage to other internal organs, and even death.

Owing to the nature of the materials and the operations of processing them, some degree of potential hazards to man accompanies all stages of the manufacture, handling and operation of chemical rocket propulsion systems, their components and the missiles or space systems which they power. That is to say, that with all these operations, there is always some level of risk of the occurrence of an explosion. Because of this ever present risk, however small it may be at some stages of the overall operation, one must take precautions to assure a minimum risk of explosions or, should an explosion occur, one must plan operations and facilities to assure a minimal hazard to men working in the areas through which the explosion blast wave will propagate. To make such plans, it is necessary to be able to estimate the energy content of any possible explosion blast wave and also to define the expected effects on man of exposure to blast waves, when their energy content varies over wide ranges. The intent is to provide herein the information needed for adequate planning. Therefore, methods of estimating the strength of shock waves are reviewed, followed by criteria which relate man's responses to shock waves of varied strengths, together with suggestions for their use. Finally, there is limited discussion of the problems associated with planning facilities and operations. Since large space vehicle systems are the potential sources of explosion blast waves of greatest energy content, emphasis has been placed on them. However, the estimation or measurement methods described are applicable to explosions of any potential source strength.

A space vehicle explosion which results from a mission abort, or from an unintentional component malfunction, is one of the most dangerous of all the environmental considerations which must be assessed during the design of a space vehicle system. The resultant explosion initially creates a relatively compact volume of high energy gases. The outward expansion of these gases creates a severe, high magnitude (shock) pressure wave which travels initially at supersonic speed. The front of the shock wave, under ideal conditions, forms a sphere with its center at the site of the explosion. Immediately behind the front is a region of high velocity, high temperature air flow. On the shock front, the pressure, temperature, and density rise very suddenly to values much greater than the ambient atmosphere and then decay to values lower than ambient conditions, and the air flow will then reverse its direction. Eventually, the pressure, density and temperature will return to ambient conditions.

The blast parameters of interest to damage and hazards evaluation are discussed and presented in graphical form in the previous sections of this chapter. These sections also present information on the explosive equivalencies of several propellants, and methods for estimating the blast effects of explosions.

2-11 CRITERIA FOR EXPOSURE OF PERSONNEL TO BLAST (SHOCK WAVE) (References 57, 58, 59)

Injury to man from exposure to the blast wave generated by an intentional or accidental explosion depends primarily upon:

a. the pressure pulse from the explosion

b. the mass movement of the air, that is, the blast winds attending the pressure variations

c. the results of the interaction of these phenomena with the human target and with his immediate environment.

In presenting and applying blast criteria, four categories of damage to man are used and are described below.

2-11.1 PRIMARY BLAST EFFECTS. These are injuries caused by variations in environmental pressure caused by an explosion and include both the primary pressure pulse and its reflections from structures or objects near the man. The pressures are customarily expressed in pounds per square inch (psi) above or below the pressure existing before the explosion. The damage to man is related to a variety of factors such as the rate, character and magnitude of the pressure rise and fall and the duration of the several phases of the pressure pulse.

2-11.2 SECONDARY BLAST EFFECTS. This area includes the injuries which are the result of the impact against the human body of penetrating and nonpenetrating missiles energized by the blast winds. The factors of importance to determination of the hazard are missile velocity, mass, size, shape, composition and density and the properties of the specific regions or tissues of the body experiencing the missile impact.

2-11.3 TERTIARY BLAST EFFECTS. These effects include damage which results from the physical displacement of the man by blast shock and winds. The seriousness of the injuries depends on the magnitude of the accelerative load imposed upon the human body and its parts; the decelerative experience—particularly where violent impacts with solid structures are involved—and the portions and areas of the body concerned. Thus, the time-history of displacement during both acceleration and deceleration are important determinants of damage. Frequently, a less precise parameter—velocity at impact—is quite useful for the assessment of damage potential and has the virtue of simplicity.

2-11.4 MISCELLANEOUS BLAST EFFECTS. This group of blast effects include exposure to ground shock; exposure to dust arising from the earth's surface or walls of structures; and temperature phenomena including thermal radiation, compression and aerodynamic heating, contact with hot dust and debris and conflagration heat from blast-produced fires.

2-11.5 THE NATURE OF BLAST INJURIES (SUMMARY). The major effects on man, the injuries that accompany blast exposure, are summarized below.

2-11.5.1 Primary Blast Injury. Damage is most marked in body regions where the great variation of tissue density is found, in particular, these are the air-containing organs of the body. Therefore, the eardrums, the sinuses and the lungs, as well as the nearby soft tissues are especially sensitive to blast damage. Lung damage of the kind that results in "air" bubbles reaching the general circulation, including the vessels of the heart and brain, is most dangerous and usually is fatal within a few minutes. Suffocation from lung hemorrhage, and edema accompanied by heart failure from lack of oxygen or from excess carbon dioxide accumulation can occur early. Untreated bleeding and bruising of the lung can result in pneumonia. Bruising of the heart, the liver, spleen and abdominal organs, with areas of hemorrhage and rupture of hollow organs can occur.

2-11.5.2 Missiles (Secondary Blast Injury). Missiles that penetrate major body cavities and damage critical organs—the heart, liver, spleen, other abdominal organs, the eyes and brain—are most injurious and frequently require early surgery to avoid fatalities. Nonpenetrating missiles impacting the chest wall with sufficient force may produce bilateral lung lesions very similar to those of exposure to primary blast and result in early fatality. Skull fracture, concussion, rupture and hemorrhage of the liver and spleen and skeletal fracture can be very dangerous, as can crushing injuries from heavy masses of masonry and other building materials. Immediate, intensive medical care is highly desirable and surgery may be essential.

2-11.5.3 Displacement. Displacement damage may be either of two types:

a. a differential displacement of body parts, resulting in the loss of a hand or limb

b. a displacement of the entire body with the decelerative experience being the most hazardous phase. The trauma produced is similar to that found in autombile and aircraft accidents and requires similar medical treatment and care.

2-11.5.4 Combined Effects (Combinations of Injuries). In practice primary, secondary or tertiary effects of blast seldom occur separately. Usually an explosion blast produces these effects in all possible relationships. Practical experience is illustrated by three cases reported from the Texas City Disaster of 16-17 April 1947. An engineer sitting at his desk in an office, with his right side toward a window a few feet away, was blown under a table. He was completely "blinded" by flying glass and was dazed but not unconscious. He reported chest pain, coughed blood from time to time for a week and suffered the following injuries: penetrating wound of the right eye, multiple lacerations of the right side of the face with severance of the facial nerve and parotid duct; lacerations of the neck, eyelids, and both lower extremities; perforation of the right eardrum and blast injury to the lung. The second case was a 37 year old pregnant woman, standing in the open near the sea train with her left side toward the ship. She felt the blast and saw debris flying through the air in all directions before she was knocked unconscious by a flying missile. When she "came to," she was in water up to her waist and part of her clothes had been blown off. Her injuries were: severe laceration of the left leg; laceration of the scalp; mild head injury; perforation of the left eardrum; spontaneous abortion; minor abrasions and contusions. The third case was a 39 year old male. He was standing at the end of Pier O facing the burning ship. When the explosion occurred, he was thrown upward so high he could see over Warehouse O; he was blown laterally into the water near the sea train installation. He did not lose consciousness and was able to swim to land. Most of his clothes were blown off. His injuries were: perforation of both eardrums; severe scalp lacerations; severe laceration of the left arm; left ulnar paralysis; and laceration of right foot. All together, the Texas City experience, about 560 persons were killed or missing, 800 persons were hospitalized and between 3,000 and 4,000 other less serious casualties occurred. The disaster illustrates well the catastropic character and also the nature of blast injuries.

2-11.6 THE BLAST HAZARD CRITERIA. Although there have been many field observations and controlled experimentation, the criteria for estimating human tolerance to blast-induced environmental variations are considered tentative. Discussion of the use of these criteria appears in sub-section 2-11.7 and a discussion of the limitations and precautionary considerations that apply to the tentative criteria is included in section 2-11. The tentative working criteria are given below. The pressure levels indicated are for typical shock waves.

Atypical pressure waves may arise in explosions when the explosive deflagrates or detonates low order or when the air through which the pressure wave propagates is dust laden. In contrast to the typical shock wave with its rapid rise (microseconds) to peak pressure and exponential-like decay to ambient levels, the atypical explosion produced pressure wave has a slow rise to peak (taking milliseconds and tens of milliseconds) and this rise may be stepped or smooth. The atypical pressure wave also usually is characterized by a flatter decay.

Tolerance is estimated to increase by about a factor of 2 for pressures rising to a maximum in two fast steps and by factors of 3 to 5 for waveforms rising smoothly to a maximum in 30 or more milliseconds.

2-11.6.1 Blast (Long Duration)

a. Eardrum Failure

Threshold	5 psi (2.3 psi)*
50 percent	15-20 psi (6.2-8.0)*

b. Lung Damage,

Threshold	10-12 psi (4.4-5.1 psi)*

c. Lethality

Threshold	30-42 psi (11-15 psi)*
50 percent	42-57 psi (15-18 psi)*
Near 100 percent	57-80 psi (19-24 psi)*

2-11.6.2 Nonpenetrating Missiles (10-lb Object)

a. Cerebral Concussion

Mostly "safe"	10 ft/sec impact velocity
Threshold	15 ft/sec impact velocity

b. Skull Fracture

Mostly "safe"	10 ft/sec impact velocity
Threshold	15 ft/sec impact velocity
Near 100 percent	23 ft/sec impact velocity

2-11.6.3 Penetrating Missiles (10-gm Glass Fragments)

a. Skin Lacerations,

Threshold	50 ft/sec impact velocity

b. Serious Wounds

Threshold	100 ft/sec impact velocity
50 percent	180 ft/sec impact velocity
Near 100 percent	300 ft/sec impact velocity

2-11.6.4 Impact, Standing Stiff-Legged

a. Mostly "Safe"

No significant effect	8(?) ft/sec impact velocity
Severe discomfort	8-10 ft/sec impact velocity

b. Injury

Threshold	10-12 ft/sec impact velocity
Fracture threshold	13-16 ft/sec impact velocity

2-11.6.5 Impact, Seated

a. Mostly "Safe"

No effect	8(?) ft/sec impact velocity
Severe discomfort	8-14 ft/sec impact velocity

b. Injury, Threshold 15-26 ft/sec impact velocity

*The figures in parentheses represent overpressures that on normal reflection will give the maximal value of pressure noted before the parenthesis.

2-11.6.6 Skull Fracture from Head Impact (see also 2-11.7.6)

Mostly "safe"	10 ft/sec impact velocity
Threshold	13 ft/sec impact velocity
50 percent	18 ft/sec impact velocity
Near 100 percent	23 ft/sec impact velocity

2-11.6.7 Total Body Impact (See also 2-11.7.7)

Mostly "safe"	10 ft/sec impact velocity
Lethality threshold	20 ft/sec impact velocity
Lethality 50 percent	26 ft/sec impact velocity
Lethality near 100 percent	30 ft/sec impact velocity

2-11.6.8 Non-Line-of-Sight Thermal Burns. No criteria are available for thermal burns caused by hot, dust-laden air moving at high velocities.

2-11.6.9 Dust Asphyxia. No criteria are presented and each case will require separate study to determine possibility of dust asphyxiation (reference 59).

2-11.7 APPLICATIONS OF BLAST HAZARD CRITERIA (MAN). The earlier sections of this chapter on blast and fragmentation describe the methods for estimating the physical parameters of the blast (shock) waves associated with intentional or unintentional explosions. Numerous charts and nomograms are given for use in making the desired estimates of the physical parameters. All of these tools should be used as needed.

2-11.7.1 Fast-Rising Overpressures of Long Duration—Criteria. On the assumption that many of the explosions associated with chemical rocket propulsion systems will fall in the fast rising category (rise time measured in small fractions of a millisecond or a few microseconds) those criteria are considered to be quite important. The criteria proposed cover a range of effects from threshold eardrum rupture to near 100% lethality of the exposed persons.

2-11.7.1.1 Eardrum Rupture. On the assumption that threshold injury is the maximum operational, adverse effect acceptable, the peak overpressure compatible with threshold eardrum rupture is 5.0 psi. This overpressure will be present at distances of approximately 1150 ft from an explosion of 500,000 lbs equivalent TNT and about 2200 ft from one of about 3,300,000 lbs equivalent TNT (see Figures 2-19 and 2-65).

Persons located at distances greater than those given above will not be subjected to more than a threshold hazard of ruptured eardrums if they are in open space far away from all reflecting walls or objects. If, however, persons are near a large reflecting surface so that the incident and reflected pressure pulses seem to act as a single pulse, the maximum allowable overpressure range is 2.3 to 2.5 psi which gives a maximum reflected peak pressure of 5.0 psi. Examination of Figures 2-19 and 2-65 shows a pressure of 2.5 psi about 1800 ft from a source explosion of 500,000 lbs equivalent TNT and about 3400 ft from 3,300,000 lbs equivalent TNT.

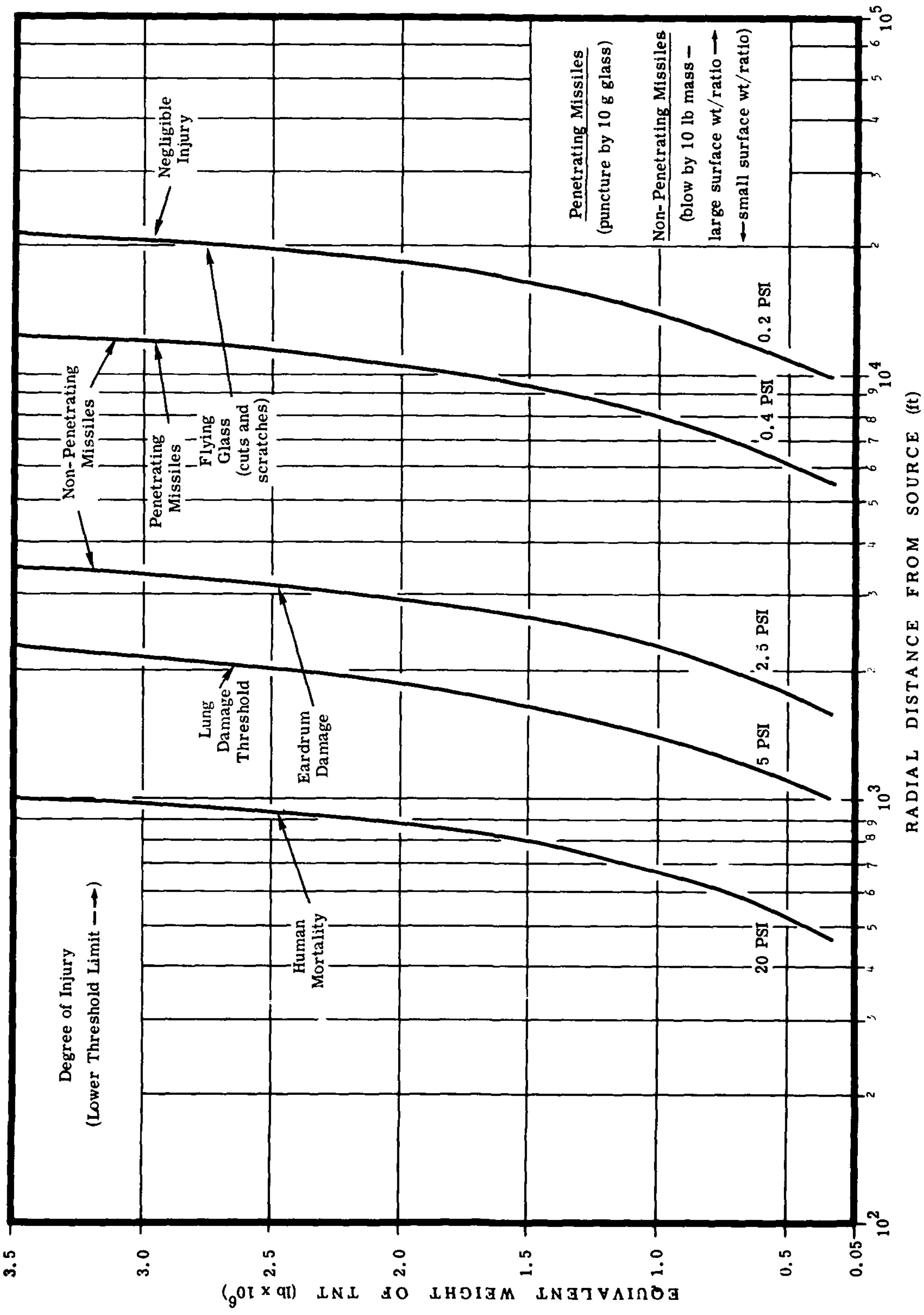


Figure 2-65 Overpressure Injury Criteria

One gains an impression of the rate of increase of hazard (eardrum rupture) by noting that at a maximum pressure of about 15 psi, about 50% of exposed eardrums will rupture. The effects of reflected pressure pulses are of great importance and must receive full consideration in the design of protective revetments, buildings, etc.

2-11.7.1.2 Lung Damage. The peak overpressure consistent with assuring only threshold lung damage is around 12 psi. Pressures of about 5.0 psi incident result on reflection in peak pressures around 12 to 15 psi. Figure 2-19 shows the distances from source explosions of varying strength at which pressures of 5 to 15 psi will be found. Again the effects of reflected pressure pulses are important and should receive detailed consideration in the design of all protective facilities.

2-11.7.1.3 Lethality. Lethality, as considered here, is essentially a continuation of lung damage, the increased damage producing death. The minimum lethality threshold pressure is about 30 psi for exposure to a direct non-reflected pressure pulse and a pressure pulse of about 11 psi reflecting to give 30 psi maximum pressure is also threshold for lethality. Thus, a pressure of 20 psi has been selected as the limiting pressure about which lethal effects occur. The distances from the exploding source at which a pressure of 20 psi is found for the range of equivalent weights of TNT are shown in Figures 2-19 and 2-65. Note that lethality for humans changes from 50% to nearly 100% as the pressure pulse increases in strength from 42-57 psi to the 57-80 psi range.

2-11.7.1.4 Atypical or Disturbed Wave Forms of Long Duration. The allowable pressures described above may be increased under certain circumstances. If the pressure rises to a maximum in two fast steps, the pressures given in 2-11.7.1.1 through 2-11.7.1.3 above may be doubled and if the maximum pressure is achieved by a uniform, smooth rise extended over 30 milliseconds or more the allowable pressures may increase by a factor of 3 to 5. The possible implications of exposures to atypical wave forms of the pressure pulse will be considered in sub-section 2-11.7.5.1.

2-11.7.2 Nonpenetrating Missiles (10-lb Object)

2-11.7.2.1 Cerebral Concussion. In this case, injury is caused by the impact of large objects (10 lbs) against the human head. Impact velocities of 10 ft/sec or below are considered generally safe. Increase of the impact velocity to 15 ft/sec results in a threshold incidence of concussion. Large objects (10 lb) may be expected to achieve velocities of 10 ft/sec in areas where the blast pressure peaks (direct) are on the order of 2.2 to 2.5 psi. The distances from a source explosion at which these pressures may be expected can be determined from Figures 2-19 and 2-65 for varied equivalent weights TNT. These curves may be used to define the inner limits of areas which can be occupied by personnel outside of protective structures.

2-11.7.2.2 Skull Fracture. This injury is closely allied to cerebral concussion and the mostly "safe" and threshold impact velocities (10 ft/sec and 15 ft/sec) are the same as for concussion. It should be noted that an impact velocity of 23 ft/sec induces skull fracture in nearly 100% of exposed persons. Personnel may not be allowed outside protective structures in areas where these hazards exist.

2-11.7.3 Penetrating Missiles (10-gm Glass Fragments).

2-11.7.3.1 Skin Lacerations. These unpleasant but usually not severely dangerous effects are the result of impacts of small solid fragments (glass, metal, etc.) of materials on the skin at impact velocities around 50 ft/sec when their mass is about 10 grams. These impact velocities and hence those hazards can be expected where the blast pressures are about 0.4 to 0.6 psi (see Figure 2-19). Personnel should be protected in areas where the blast pressure exceeds 0.4 psi.

2-11.7.3.2 Serious Wounds. The threshold for serious wounds caused by penetrating solid objects (10-gm glass, metal, etc.) is at an impact velocity of 100 ft/sec. An impact velocity of 180 ft/sec causes serious wounds in about 50% of the exposed persons. An impact velocity above threshold but below the 50% serious wounds regions—115 ft/sec—is to be expected in areas where the blast pressures are about 2.2 psi.

2-11.7.4 Impact Standing Stiff-Legged. These criteria are concerned with the impact of a man falling feet first and stiff-legged and are probably rare events in connection with blast from rocket propulsion systems. It would be possible for a man to impact a solid wall feet first which would approximate these conditions. Note that impact velocity for real injury is about 10 ft/sec or just above and similar to other impact velocities that produce injuries to man.

2-11.7.5 Impact Seated. Comments similar to those in Section 2-11.7.4 above apply here as well.

2-11.7.6 Skull Fracture from Head Impact. These criteria apply to the whole man, impacting "head on" with a solid structure. Note that the impact velocities for a similar degree of injury are the same as for a 10-lb object impacting the head. A man weighing 160 lbs may be accelerated to the velocity of 10 ft/sec in a distance of 10 ft where the blast pressure is about 2.0 psi. If the blast pressure is abound 4.3 psi the 160 lb man achieves a velocity of 10 ft/sec in one foot. The distance from an exploding source at which pressures of 2.0, 2.2, and 2.5 psi occur can be found in Figure 2-19. Certainly operating personnel must be shielded from exposure to these hazards—and the blast pressures inducing them.

2-11.7.7 Total Body Impact. These criteria pertain to impact of the whole human body against a solid structure when the part of the body making the impact contact is other than the head. As for the case of head on impact the mostly "safe" impact velocity is 10 ft/sec and a 160 lb man may have this velocity imparted to his body in a distance of 10 ft where the blast pressure is about 2.0 psi. The lethality threshold is at an impact velocity of 20 ft/sec with a probable 50% lethality at an impact velocity of 26 ft/sec. The operational approach should seek to avoid human exposures that reach lethality threshold and this means no exposures to blast pressures that will part a velocity greater than 10 ft/sec to the human body or no exposure to blast pressures exceeding about 2.0 psi. See Figure 2-64 for distances from explosions of different equivalent weights of TNT at which overpressure around 2.0 psi are to be expected.

2-11.7.8 Non-Line-of-Sight Thermal Burns. No criteria are available, so that one can only suggest that this hazard may frequently exist and that care must be exercised in each particular case to see that the hazard is controlled.

2-11.7.9 Dust Asphyxia. Here again, there are no general criteria available and caution must be exercised to avoid this hazard in the operation of each particular system or installation.

2-11.7.10 Other Factors. It has been suggested that the limit or border of the controlled areas around sites where chemical rocket propulsion systems are operated be placed at distances such that a blast pressure of 0.2 psi will not be exceeded. This distance is recommended to avoid minor injuries from the fragmentation of ordinary glass. This pressure is to be expected at radial distances between 10,000 ft and 21,000 ft from the source explosion for the ranges of equivalent weight of TNT shown in Figure 2-65. Note, however, that as stated in Sub-section 2-8.2.6.1, window breakage can occur at pressures as low as 0.03 psi and atmospheric focusing effects play a large part in determining the ranges to which pressures below 1 psi extend. Thus, in establishing window breaking criteria and distance, great care must be exercised in the use of pressure-distance curves, and all factors, including weather conditions must be considered. In addition, it has been suggested that all personnel inside the controlled area be given protection when in any area where the blast pressures may exceed 0.4 psi. The radial distances from the source explosion at which this overpressure value may be expected from a range of equivalent weights of TNT are shown in Figures 2-19 and 2-65.

2-11.8. LIMITATIONS AND PRECAUTIONS RELEVANT TO BLAST HAZARD CRITERIA. First, one should note that the blast hazard criteria cited earlier in this document were identified as "tentative criteria." Furthermore, those persons engaged in the investigations that provide the bases for all current criteria express the present status in these terms; "a beginning has been made in formulating tentative biological criteria for estimating human hazards associated with exposure to blast phenomena" (reference 59). If then, the state of our knowledge, as regards blast hazard criteria, is as just described, one must expect many deviations from the criteria in the course of practical exposure to blast wave fields. A few of the major "unknowns" or "uncertainties" as regards blast hazard criteria will be pointed out but the reader also should consult reference 59 which contains some 117 additional references relevant to these problems.

2-11.8.1 Uncertainties Related to Primary Effects (Pressure). It is now established that the effects of blast induced air pressure variations, manifested as lung damage and lethality are related to the rate, the magnitude and the duration of the pressure rise and fall. Also biological tolerance, as regards major effects, are different when the pressure pulse wave form deviates from the classical or near-classical configuration (for details see reference 59 and the numerous references cited therein).

2-11.8.1.1 Classical or Near-Classical Wave Forms. Eardrums may be ruptured by the application of a sufficient under or overpressure but the criteria presented herein are based on application of overpressure only. The available data obtained on man has been supplemented by data from animal studies. The range of pressures rupturing eardrums is wide but all bodies of data suggest the 5 psi value as the threshold pressure for eardrum rupture. Certain animal studies indicate fast rising pressure pulses (classical) produce rupture in 50% of eardrums between 10–12 psi, whereas slow rising pulses produce this amount of eardrum ruptures at pressures from 32 to 36 psi. Therefore, the pressure range 15 to 20 psi has been selected for the "criterion range" for rupture of 50% of the exposed, adult human eardrums.

The current criterion overpressure for threshold lung damage of 10 to 12 psi has recently been lowered from a value of 15 psi. This change is based primarily on extensive animal data. Again there is apparently a significant difference between "fast" rising (classical) pressure pulses and "slow" rising pulses of the order of 2 to 1 and the criterion value relates most closely to the lower pressure amplitudes relevant to "fast" rising pressures because these seem more likely to occur in accidental explosions.

The current criterion values of the pressure amplitude for threshold lethality of 30 to 42 psi are also derived largely from data obtained by animal experiments. These values are for fast rising long duration pressure pulses. Some impression of the effect of duration can be obtained from the table below.

Table 2-12

Estimated Pressure for 50% Lethality for 70-kg Animals in psi at an Ambient Pressure of 14.7 psi (See reference 59, page 169)

Pulse-Duration in msec	From all Species	From Dogs and Goats
400	64	62
30	78	62
20	87	64
10	120	79
5	227	120
3	528	188

The pressure values in the table are for 50% lethality rather than threshold lethality. The table also shows that criterion pressure values are different, when derived from all animals, than when derived from large animals only—therefore body weight may be a significant factor in the determination of the biological effects of blast pressure pulses.

2-11.8.1.2 Disturbed Wave Forms. In certain exposure locations, as for example, varying distances from reflecting surfaces, stepwise increases of overpressure can occur—that is the initial incident pressure followed by the reflected pressure pulse. If the pulse separation time is short, about 0.5 to 1.0 msec for large dogs, the animal "appreciates" the pressure rise as one pulse. For longer time intervals of separation between pulses, perhaps a few msec for animals as large as man, the biologic target "sees" two separate pressure pulses. This may raise the tolerance by a factor of 2 for large animals including man. New data are required before a more precise statement of the effects of stepwise increases in overpressure can be made.

2-11.8.1.3 Other Wave Forms. Animal data and other data have shown that, when the rising phase of a pressure pulse increases smoothly or in small incremental steps, the tolerance for overpressures increases by a factor of 3 to 5. The very first phases of the pressure rise must be slow enough and small enough not to be lethal of itself. This increased tolerance is found if the pressure rise time is 20 or more msec. These observations show that in practical situations where the over-pressure rising phase is known to be slow (longer than 20 msec) and uniform, the tolerance criteria for adverse responses of man can be raised.

2-11.8.2 Uncertainties Related to Secondary Effects (Missiles). A wide variety of materials may be energized by the blast wave pressures, winds and ground shock. The hazard to man from impact of such missiles on him depends on the kind, the mass and velocity of the missile; the angle of impact; and the area or organ of the body involved. Ten gram glass missiles were used as examples of the penetrating type and a 10-lb object as an example of the non-penetrating type. The head was selected as the critical organ on impact but the liver, spleen or other organs may be equally susceptible. Therefore, the actual injury is determined by many factors and each case must be evaluated in terms of the apparent causes (or hazard source).

2-11.8.3 Uncertainties Related to Tertiary Effects (Whole-Body-Displacement). Whole-body-displacement may result from the forces applied by blast pressures, winds, ground shock and by gravity. These accelerative and decelerative experiences represent major and sometimes the most far reaching effects of blast on man. The significance of the effects depends on the magnitude of the forces; the time, distance and angle over which they are applied; the character of the contact surface and the area of the body affected. Current criteria are simply aids to assess possible decelerative injury.

2-11.8.4 Miscellaneous Effects. In this group of hazards are the possible effects of hot, debris-laden gases, compression heating, blast induced fires, burns from pieces of hot debris and inhalation of dust and other aerosols which may lead to asphyxiation. Each of these potential hazards must be assessed with respect to the specific design features of each manufacturing plant, test facility or operating site including any protective structure or like construction.

2-12 FACILITY PLANNING AND SITE SELECTION—PERSONNEL CONSIDERATIONS

In the operation of chemical rocket propulsion systems and other systems powered by them, the occurrences of an explosion and the generation of blast (shock wave) energy fields are not accompaniments of the regular routine procedures. In the launching of missiles or space systems, intentional destruct explosions may occur but they are imposed by failure of some other part of the system or phase of the operation. Otherwise, explosions are accidental, undesired and perhaps infrequent events. However, the properties of propellant chemicals in various combination always impose some potential risk of an explosion and exposure to blast fields. Owing to this fact, plans must be made to:

a. minimize the chance for explosions

b. minimize potential physical harm to operating personnel

c. avoid or minimize all risk of bodily harm to those persons who are inadvertent recipients of blast exposure simply because they live relatively near manufacturing plants, transportation routes, or the actual facilities where such systems are operated.

In addition, plans must be made to assure adequate first aid, medical treatment and medical care for any injured persons should an explosion occur despite all care taken to avoid such events. The planning considered herein relates to prevention of personnel injury and to care of personnel should injury occur. Detailed engineering procedures are not stated but the reasons for taking specific engineering, planning action are considered. These problems may be considered under "Facility Planning" which include site selection, facility lay-out and appropriate land use inside and outside the facility and under "Operations Planning" which may be subdivided into "Within-Facility Planning" and "Outside of Facility Planning." "Within Facility Planning" is directed toward protection of operating personnel and "Outside of Facility Planning" is concerned with the avoidance of damage or annoyance to persons occupying uncontrolled area surrounding a facility.

2-12.1 FACILITY PLANNING. In planning facilities for the several phases of the manufacture and the operation of chemical rocket propulsion systems to properly protect against possible hazards of explosions and blast fields, one must consider the internal facility problems and those created by blast wave propagation into areas outside but surrounding the facility. Three problem areas are significant:

a. site selection

b. facility layout

c. land use

2-12.1.1 Site Selection. Many factors enter into site selection, peak overpressure being an important one. Let us assume that a peak blast pressure of approximately 0.2 psi is selected as the maximum allowable pressure in uncontrolled areas outside facilities concerned with chemical rocket propulsion materials and systems. Figure 2-65 indicates that this pressure may be expected about 10,000 feet from an explosive source of 330,000 lbs equivalent weight of TNT and about 21,000 feet from a 3,300,000 lbs equivalent weight of TNT explosion source. To satisfy this peak pressure requirement for the 3,300,000 equivalent weight TNT one needs a radius of about 4 miles from the source or the diameter of the restricted (controlled) area would be of the order of 8 miles. This requirement demands large areas of land, which can be acquired and controlled to assure adequate safety to persons outside the facility. Thus site selection must take these requirements into consideration and it would be highly desirable to have minimum population density in the areas surrounding the facility. Site selection must also assure suitable terrain and other factors for the construction of the varied special buildings, equipment installations and personnel quarters within the borders of the facility.

2-12.1.2 Facility Layout. Blast pressure may be the factor that determines the type of construction used within a facility as well as the location of buildings occupied by personnel doing the work required by the operation. Blast pressures around 2.2 to 2.5 psi create danger from penetrating and nonpenetrating missiles and approach the threshold for potential ear damage. Over the range of equivalents weights TNT given in Figure 2-65 a pressure of 2.5 psi is to be expected at radii of 1,600 to 3,400 ft from the explosion source. Certainly at distances from the source shorter than these, special protective structures will be required for operating personnel.

2-12.1.3 Land Use. Some additional protection could be provided for persons not affiliated with the facility by locating supporting operations or facilities near but outside the border of the primary facility. The potential use of bordering land for such purposes should be considered a part of facility planning.

2-12.2 OPERATIONS PLANNING. Once a site has been selected and the general facility layout sketched, a plan should be formulated for the operations to be carried out. Of course a preliminary operations plan may be needed for site selection but a more detailed plan is required to guide the final facility layout. Protection from blast pressures within the facility will be an important factor in the final construction plan. Blast pressures and their control are also factors to be considered in terms of their effects on people outside the facility.

2-12.2.1 Within Facility Planning. The boundary line, for facilities working with chemical rocket propulsion systems, their materials, their components or the systems they propel, is placed to assure blast wave pressures at this line of approximately 0.2 psi. Since this pressure represents the separation between "significant" and "negligible" personnel injury (flying glass and other small missiles) all areas inside this boundary are within the region "significant" personnel injury. Therefore, all work areas inside the facility boundary must be planned to provide the degree of blast protection for personnel demanded by the blast pressure level expected in each work area. Although an explosion and an accompanying blast wave are either the result of an emergency situation or an accident, they may occur and the operational plan must provide for the necessary rescue, first aid and medical care of injured personnel.

2-12.2.1.1 Blast Protection (Personnel). In areas where the blast pressure lies between about 0.2 psi and 0.75 psi protection from injury by glass missiles requires windowless construction, using, otherwise, ordinary construction methods. In the regions where the blast pressures increase from 0.75 psi to about 2.0 psi, strengthened, windowless construction is required for personnel protection. Wherever the blast pressures exceed 2.0 to 2.5 psi, special protective construction is required and the construction requirements depend on the expected pressure at a given building (see Section 2-8). Wherever operational requirements permit, it is probably desirable to place structures occupied by personnel at distances from the source explosion that eliminate the need for highly specialized blast resistant structures. Each facility must consider the probable maximum strength explosion that could occur during the expected operations and formulate compatible operational plans.

2-12.2.1.2 Emergency Rescue and Care (Personnel). Since the possibility of an unwanted explosion cannot be eliminated, the operational plan should contain a specific, detailed procedure for rescue and care of personnel following an explosion. The details of this plan should be based on the maximum blast pressures to which personnel may be exposed at each particular facility. If these pressures exceed 2.5 psi, eardrum rupture and injury by fragmentary missiles may be expected. If the pressures exceed 5.0 psi, varying degrees of lung damage and impact injury are probable. The higher the expected pressures, the more severe the expected injury will be. The operational plan must provide for:

a. rescue at the earliest possible time

b. immediate emergency care or first aid

c. the necessary hospital facilities for the long term care and medical care of the severely injured

2-12.2.2 Outside-the-Facility Planning. If site selection and facility planning have provided the distances between explosion sources and people outside the facility required to achieve the 0.2 psi pressures assumed, the primary problems to be planned for outside the facility will be those created by unusual meteorological conditions. Under particular meteorological conditions blast pressure waves may be refracted and concentrated in areas outside the facility and so result in exposures to blast pressures higher than those ordinarily present. These meteorological states causing such increased pressures are specific to a given location. Therefore the operational plan must identify the times when these unusual conditions may occur and assure an operational program that minimizes the possibility of creating excessive pressure disturbances in surrounding communities.

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CHAPTER 3

FIRE PREVENTION AND PROTECTION

3-1 INTRODUCTION

This chapter contains general information applicable to the prevention of fire (or minimization of fire damage) in all propellant operations. This material is developed as a first line reference document to indicate areas of concern, methods and approaches which may be useful. Users are urged to consult specific references listed herein for more complete details. Tables 3-1 and 3-2 of this chapter as well as Volumes II and III should be consulted for specific fuel hazards, fire fighting techniques, and storage compatibility summaries.

Effective fire prevention and protection depends on more than exotic facilities or equipment. The imaginative application and utilization of procedures and personnel must be employed to prevent fires. Supervisors and managers must anticipate and be continually alert for lapses in employee performance that may compromise fire safety. (Reference 1)

3-1.1 OPERATING PROCEDURES (OP). Written detailed OP's should be used in all operations associated with propellants. They should include a chronological, task-by-task, step-by-step, approved method of accomplishing hazardous activities safely. Essential to the successful use of OP's is a management system for keeping them current so that supervisors never need to instruct or permit an employee to deviate from the OP. If accidents occur while performing to an approved procedure, work should be stopped until the cause is determined or the procedure is changed to avoid those conditions or operations leading to the accident.

3-1.2 EXPERIMENTAL WORK. All aspects of proposed or planned work should be thoroughly reviewed and each hazard evaluated so that appropriate fire safety measures can be developed concurrently with other facets of the OP's.

3-1.3 HAZARDOUS EXPOSURES. The prime consideration must be to minimize exposure of personnel to fire hazardous environments. When it is necessary for personnel to be exposed to such conditions, they should not work alone. The "buddy system" or an acceptable variant will be employed in all areas or in operations designated as fire hazardous.

3-1.4 FIRE SAFE WORK AREAS. An orderly, clean, controlled environment is basic to fire safety. Frequent housekeeping inspections are required in all areas. Specific attention should be paid to those items which can result in a chain of events leading to fire. Every effort should be exerted to provide fire safe work areas.

3-2 FIRE HAZARD PROPERTIES OF PROPELLANTS

3-2.1 COMBUSTIBLE MATERIALS. As used in this paragraph combustible materials are those propellant ingredients which are capable of combustion. Combustible materials used in the preparation of propellants fall into two general categories, namely oxidizers and fuels.

3-2.1.1 Oxidizers. Oxidizers possess a ready supply of oxygen or other elements (such as fluorine and chlorine) which can be liberated by heat pressure, or contact with other substances. In general, oxidizers should be kept in a controlled environment in a pure state or condition and protected from contact with all substances except those which are known to be compatible.

3-2.1.2 Fuels. Common rocket solid and liquid fuels contain hydrogen, carbon, sulphur, metals, hydrocarbons, or boron compounds. All fuels undergo oxidation depending upon conditions. Some of the boron containing fuels will spontaneously ignite when in contact with air at ambient temperature. Each fuel must be protected from conditions and materials which could oxidize that particular fuel. (Reference 2)

3-2.2 MONOPROPELLANT.

3-2.2.1 Liquid Monopropellants. Liquids at ambient temperatures are relatively unstable individual compounds or single tank mixtures which reactively undergo auto-decomposition. These may or may not contain all elements necessary for combustion. Accordingly, they are flammable in vapor concentrations up to 100%. They They should be protected from contact with air and other oxidizers. (Reference 3)

3-2.2.2 Colloid Monopropellants. Generally mixtures of nitrocellulose, nitroglycerine, plasticizers, stabilizers and other special ingredients are ignitable in the finished and unfinished conditions. Granules and dust present special hazards for friction and spark ignition. (Reference 4)

3-2.2.3 Composite Propellants. Mixtures of fuels, binders, and oxidizers with or without other ingredients are ignitable in the cured or uncured state and should be protected from unintentional heat, pressure, and contact with incompatible substances. Wastes in the form of smears and granules are particularly hazardous. Numerous ignitions have occurred in machining processes.

3-3 COMPATIBILITY OF MATERIALS

As used in this volume, compatibility of materials refers to materials which in close proximity to or containing the propellant will have no undesirable reaction with or upon the propellant.

3-3.1 STORAGE COMPATIBILITY.

3-3.1.1 Contractor Storage and Compatibility Standards. Details on the storage compatibility standards for ammunition and explosives (including propellants and their ingredients) are found in Volumes II and III of this publication and in Reference 5.

3-3.1.2 Compatibility During Transit Standards. The standards of compatibility applicable during transit are found in Reference 6.

3-3.1.3 Containers. Systems for storing, transferring, handling, and processing should be designed of compatible materials. In addition to the vessel structures (tanks, bins, drums, pipes, hoses, pumps, etc.) associated materials which may accidentally come in contact with propellants or propellant ingredients should also be compatible. Particular care should be used in the selection of lubricants, hydraulic fluids, paints, solvents, absorbants, and cleaning agents.

3-4 CONTAMINANTS

Some propellant ingredients are subject to hazardous contamination such as:

a. Air, gases, particles, and fumes

b. Water and water soluble materials

c. Animals, animal products, and vegetative materials.

3-5 IGNITION SOURCES

The relative ease of ignition of gaseous combustibles is known and appreciated. Dusts, thin films, filaments, and granules may also be ignited under a wide variety of conditions. Care must be taken to avoid the application of pressure, temperature or other force in such a manner as to permit the formation of localized "hot spots" and development of viscous flow or intercrystalline stress. In general any forces which may result in the focusing of energy in a small area can result in ignition. As an example—a propellant may require a drop of X number of inches to initiate in a standard drop test mechanism and yet ignite accidentally when a box is dropped a fraction of this distance provided the force of the drop is concentrated on a confined area such as a nail head. The following are all potential ignition sources:

3-5.1 ELECTRICAL.

a. Spark discharge or arcing

b. Electrostatic discharge

c. Short circuit (or other resistance heating)

d. Electromagnetic radiation.

3-5.2 OPEN FLAME.

a. Matches or lighters

b. Pilot lights

c. Welding or cutting torches.

3-5.3 FRICTION.

a. Drive belts and pulleys

b. Poorly lubricated machinery

c. Impact between hard materials.

3-5.4 SPARKS.

a. Engine Exhausts and Electrical Systems

b. Tools

c. Cigarettes

d. Shoe nails striking other metal.

3-5.5 SELF OXIDATION. (Reference 7)

3-6 DESIGN CRITERIA

3-6.1 FACILITIES. (References 1, 7, and 8)

Fire prevention should be one of the primary objectives during the facility design effort. Design criteria should therefore encompass all aspects of standards developed to control the hazards inherent in handling, moving, storing and using flammable materials or their ingredients. Consideration should be given to standards pertinent to separation of installations, compatibility of materials, electrical equipment, ventilation and heating systems recommended for use with the specific hazards associated with the particular propellant or ingredients thereof which are being processed.

3-6.2 BUILDINGS.

3-6.2.1 Construction Materials. External wall and roof coverings should be noncombustible and of light weight materials that will not form dense missiles, should an explosion occur. Flooring material should withstand repeated washing with hot water, and it should be nonsparking and conductive in those occupancies where a mechanical or electrical spark may be hazardous due to exposed explosives or flammable vapors, gas or combustible dusts. Interior materials also should be noncombustible.

3-6.2.2 Design.

3-6.2.2.1 Interior Finishes. Finishes on interior surfaces of operating buildings should be smooth, free from cracks and crevices, having joints taped or sealed, and if painted, covered with a hard gloss paint to facilitate cleaning and to minimize the impregnation of finished wall and ceiling surfaces. Use of flush-type construction for wall openings such as doors and windows will further aid cleaning and eliminate voids where combustibles may accumulate. Where frequent washdown of the interior buildings is required, floors should be sloped and adequate drains and catch basins provided. Cove bases at the junction of walls and floors will also facilitate cleaning. Fasteners (screws, nails, bolts, etc.) should be countersunk and sealed over.

3-6.2.2.2 Construction. Unless necessitated by process requirements, buildings should be one story and without basements or interior wells. Fire walls should be used to reduce fire propagation within large buildings. The number and size of openings in fire walls should be kept to the minimum required for operations. Such openings should be protected in accordance with NBFU Pamphlet No. 80M. (Reference 9)

3-6.2.3 Electrical Equipment.

3-6.2.3.1 Minimum Standards. The type and installation of electrical equipment and wiring, as a minimum, should comply with the provisions of the National Electric Code.

3-6.2.3.2 Hazardous Locations. Electric motors, lighting fixtures, and other electrical devices should not be located in rooms or buildings containing combustible dust, vapor from which explosives may condense, or flammable vapors or combustible dusts which may form explosive or flammable mixtures with air. When, for practical reasons, such installations are necessary, the equipment or device should be approved for use in Class I or II hazardous locations, and should be dual rated if both hazards exist. If dual rated equipment is not obtainable and the hazards of one type of air contaminant is greater than the other, equipment approved for the more hazardous condition should be used.

3-6.2.3.3 Lamps. When it is necessary to install Class I, II, or dual rated lighting fixtures in hazardous locations, lamps which will not raise the temperature of exposed surfaces above 228°F should be used. NOTE: These provisions are not intended to preclude the installation and use of electrical grounding circuits in explosives operating buildings.

3-6.2.4 Ventilation. Combustible particles, dust, fumes, vapors and gases should be removed from buildings and collected, dissipated or destroyed as appropriate. When exhaust systems are used, they should intake at the hazard source and be electrically bonded and grounded. Exhaust systems should be cleaned frequently and serviced regularly. Exhaust systems should be designed to work efficiently under the most adverse weather conditions during which it is expected that operations would continue. See also "Disposal and Decontamination" sections in this volume and specific recommendations on propellants in Volumes II and III of this publication and in References 10 and 11.

3-6.2.5 Heating.

3-6.2.5.1 Radiation. Radiation is the preferred means for heating buildings. Exposed radiating surfaces in the form of smooth pipes or fin-type radiators are suitable because of the ease with which they can be cleaned. Shielding or guarding should be used if radiating surfaces are sufficiently hot to injure or startle personnel on accidental contact.

3-6.2.5.2 Heating Pipes. Heating pipes may be imbedded in walls and floors. In the case of the floor installations, however, special care must be taken to assure that the floor is kept free from cracks, crevices, and other imperfections which would allow combustibles to collect around subsurface piping.

3-6.2.5.3 Convection Heating. If convection heating is used, heating units, with fans or blowers, should be located in nonhazardous areas. Heated air should be transmitted to hazardous locations by duct work. Effective means should be provided at all duct openings in hazardous locations to prevent contamination of the duct work during periods when the fan or blower is not operating. The design and installation of duct work should be such that it will not spread fires or combustibles from one area to another.

3-6.2.6 Location.

3-6.2.6.1 Building Sites. In selecting building sites, appropriate consideration should be given to protection from natural hazards such as lightening and floods. Depressions where fogs and explosive vapors will persist should be avoided if possible. When movement from building to building is required, building sites on a continuous level offer both operational and safety advantages. Separation from brush and forested areas reduce natural fire hazards and facilitate protection against vandalism and arson.

3-6.2.6.2 Access. Facilities should be accessible to fire fighters from different directions so that winds will not defeat them.

3-6.2.6.3 Separation. Buildings should be so separated that their contents or processes do not jeopardize other buildings and public places.

3-6.2.7 Fire Extinguishing or Supressing Systems. Water (fog, spray, sprinkler or deluge), carbon dioxide, dry chemical, inert gas, or other fire extinguishing and suppressing systems should be installed to protect personnel, and to prevent loss of equipment, facilities, material, and capability. Special attention must be given to the fire extinguishment to insure that it is appropriate. Some extinguishing agents, if improperly used, will intensify the fire. See Tables 3-1 and 3-2 of this chapter for a summary of the various fire fighting techniques and types of fires to which these methods are applicable. (Reference 12)

3-6.3 CONTAINMENT. Through forethought and provision, many practical methods of containment may be used to prevent fires or to reduce their intensity and involvement. Such methods include:

a. Diking - areas around storage facilities

b. Venting - normal and emergency

c. Jellying - use of agents to increase viscosity of flammable liquids

d. Absorption - use of porous materials to reduce volatilization of flammables

e. Dilution - to reduce a liquid's concentration or modify its viscosity to render it less flammable

f. Blanketing - using flux or inert materials to prevent air contact.

3-7 CONTROL METHODS

3-7.1 FIRE PREVENTION. The term fire prevention as used in this chapter refers to methods and activities which should be developed to reduce the probability of the occurrence of fire, resultant damage and personnel injury.

3-7.1.1 Program. The prime prerequisites for an effective fire prevention program should be hazards analyses, operating procedures, training, alertness,

Table 3-1

Solid Propellant, Explosives, and Propellant Ingredient Characteristics[1]
(Summary for Fire Protection Guidance and Related General Information)

Propellant or Item	Formula/Synonym[2]	Storage Compatibility Group[3]	Explosives Hazard Class[4]	Toxicity TLV/EEL[5]	DoT Classification and Shipping Label[6,7]	Explosion and Fire Hazards[1]	Fire Control Methods and Measures[2, 8]
ALPHA HMX	(See Cyclotetramethylene Tetranitramine)	---	---	---	---	---	---
Aluminum[1]	Al/none	C	1	15 mg/m^3 50 ppm/ft^3 of air.	Not regulated by DoT in usual form, but U.S. Coast Guard regulates as a hazardous article. IATA classes it as a flammable solid, yellow label.	Moderate fire and explosion hazard if exposed to heat and flame. Mixtures of Al and Cl containing solvents such as CCl_4, CH_2Cl_2 $CHCl_3$, etc., have resulted in explosion on heating.	Do not use water. G-1 or MET-L-X are capable of complete extinguishment. Dry sand if carefully placed over a pile of burning Al powder will smother flame. It is usually better to isolate the fire and let it burn out without disturbing the mass.
Aluminum Hydride[1,10]	AlH_3/none	See Note 9, 10	N/A	N/A	Flammable Solid N. O. S. Yellow Label.	Will ignite when exposed to air. AlH_3 reacts explosively with water, acids, or oxidizers. Will pick up electrostatic charge and ignite explosively. Decomposes with heat to form H_2.	Do not use water. G-1 or MET-L-X are capable of control. Inert dry powder or sand if carefully placed can be useful. Containers must be grounded when being filled and emptied to prevent ignition and explosion.
Amatols	Varying AN/TNT Composition NH_4NO_3, 80%; $(NO_2)_3$ $C_6H_2CH_3$, 20%	I	7	Variable	Explosive A.	High fire hazard as a result of spontaneous chemical reaction. A powerful oxidizing mixture. High explosion hazard due to shock or spontaneous chemical reaction.	Do not fight Amatol fire; evacuate personnel.

Ammonium Nitrate[1]	NH_4NO_3/AN, Norway saltpeter; white crystal	D	1, or Class 2 when not in original container, to Class 7 when exposed to shock or explosion.	N/A	Oxidizing Material, Yellow Label.	Moderate fire hazard by spontaneous reaction, powerful oxidizer. Severe explosive hazard when shocked, exposed to heat or spontaneous chemical reaction, self-detonating under certain conditions. On decomposition by heat, NH_4NO_3 emits toxic fumes.	Flood with water. When large quantity of NH_4NO_3 is involved, fight fire remotely. Hose streams of water should be applied from protection of barricade because of likelyhood of steam pocket explosions.
Ammonium Perchlorate[1]	NH_4ClO_4/AP; white crystal	K	1, or Class 2 when not in original container, to Class 7 when exposed to shock or explosion.	N/A, skin, eye irritant	Oxidizing Material, Yellow Label or if particle size less than 15 microns Explosive A. See specific exemption and packaging.	Moderate fire hazard. Severe explosion hazard when heated with sulphur, organic matter or finely divided metals.	Use water. Do not use fire blanket if clothing catches fire in presence of NH_4ClO_4. Only remote controlled or automatic extinguishment systems should be used on fires involving AP finer than 15 micron particle size.
Azide	(See specific compound)	M	7	Variable	Explosive A.	Severe explosion hazard when shocked or exposed to heat.	Do not fight Azide fire; evacuate personnel.
Baratol	Contains Ba and TNT in various proportions, i.e., 20:80 Baratol and 10:90 Baratol; buff color.	I	7	Variable	Explosive A.	Moderate explosion hazard. Will detonate under strong shock.	Do not fight Baratol fire; evacuate personnel.
Benite	Modified black powder containing potassium nitrate in a matrix of NC, 40%.	O	7 Class 2 when wet.	---	Explosive A.	Extreme fire hazard, will detonate when dry.	Do not fight Benite fire; evacuate personnel.
Beryllium[1]	Be/Glucinum	N/A	1	0.002 mg/m^3 of air.	Poison B. Poison Label.	Fire hazard, slight explosion hazard, severe toxicity hazard for fine powder or partially combusted material.	Water applied for fire control or flushing must be contained in temporary dike for disposal; toxic products must not enter water table or sewage systems. Wear self-contained breathing apparatus.

Table 3-1 (Continued)

Solid Propellant, Explosives, and Propellant Ingredient Characteristics[1]
(Summary for Fire Protection Guidance and Related General Information)

Propellant or Item	Formula/Synonym[2]	Storage Compatibility Group[3]	Explosives Hazard Class[4]	Toxicity TLV/EEL[5]	DoT Classification and Shipping Label[6,7]	Explosion and Fire Hazards[1]	Fire Control Methods and Measures[2,7]
BETA HMX	(See Cyclotetramethylene Tetranitramine)	---	---	---	---	---	---
BIS Compounds	Various Formulas (See specific compounds)	Variable	Variable	N/A	Explosive B; Red Label.	Variable sensitivity and fire hazard; burns without detonation.	Extinguish with foam. dry chemical or CO_2.
BIS (2, 2-Dinitropropyl) Formal	$(CH_3C(NO_2)_2CH_2O)_2CH_2$/BDNPF	N/A	N/A	N/A	Explosive B; Red Label for express or Air Shipments.	Burns without detonation; can be detonated by strong shock.	Extinguish fire with foam, dry chemical or CO_2.
Black Powder	Mixture of $NaNO_3$ or KNO_3, S, and C	O	7	Variable	Explosive A.	Will burn with explosion-like violence; very sensitive to heat, friction, and impact.	Do not attempt to fight a fire in which black powder is involved; evacuate personnel.
Boosters and Booster Aux.		B	7	Variable	Explosive A.	High explosive.	Do not attempt to fight a fire in which booster explosives are involved; evacuate personnel.
Boron Potassium Nitrate		O	7	N/A	Explosive A.	High explosive.	Do not attempt to fight a fire in which boran potassium nitrate explosives are involved; evacuate personnel.
CBS	Plastic HE consisting of RDX 84% and remainder butyl stearate with (call) 1. 5% stabilizer	I	7	---	Explosive A.	High explosive.	Do not attempt to fight a fire in which CBS explosives are involved; evacuate personnel.
Charge Igniter Assembly, for Fuses M 10	---	B	3	N/A	Explosive B; Red Label for Railway express or Air Shipments	Severe fire hazard, will burn with explosion-like violence when confined	Do not attempt to fight a fire in which charge igniter explosives are involved; evacuate personnel.

Charges, propelling not assembled to projectiles	---	J	2 or 7	N/A	Explosive B, Red Label for Railway express or Air shipments	Variable fire and explosion hazard	See package notes, bill of lading or labels.
Chlorates	Variable	K	1	N/A	Oxidizing Material N. O. S. Yellow Label.	Moderate fire hazard. Moderate explosive hazard when exposed to heat, shock.	Flood with water.
Composition A, A-2, A-3, A-4 A-5	RDX; coated with beeswax 9% (A), to 1+ % (A-5)	I	7	N/A	Explosive A.	High explosive, fire hazards.	Do not fight a Composition A fire; evacuate personnel.
Composition B and B-3	RDX, 60%; TNT, 40%/ Hexolite, Cyclotols	I	7	N/A	Explosive A.	High explosive, fire hazard.	Do not fight a Composition B fire, evacuate personnel.
Composition C	RDX, 77%; Tetryl, 3%; TNT, 4%; DNT, 10%; MNT, 5%; NC, 1%/white plastic explosive	I	7	N/A	Explosive A.	High explosive, fire hazard.	Do not fight a Composition C fire, evacuate personnel.
Composition C-2	RDX, 78.7%; plus plasticizer	I	7	N/A	Explosive A.	High explosive, fire hazard.	Do not fight a Composition C-2 fire, evacuate personnel.
Composition C-3	RDX, 77%; DNT, 10%; MNT, 5%; TNT, 4%; Tetryl, 3%; NC, 1%/ yellow plastic explosive	I	7	1.5 mg/m^3	Explosive A.	High explosive, fire hazard (more powerful explosive than TNT)	Do not fight a Composition C-3 fire, evacuate personnel.
Composition C-4	RDX, 91% plus plasticizer/light brown plastic explosive	I	7	N/A	Explosive A.	High explosive, fire hazard (more powerful than TNT. Detonates at a higher velocity than C-3; less sensitive to impact than TNT).	Do not fight a Composition C-4 fire, evacuate personnel.
Copper Chromate	$CuCrO_4$-$2CuO \cdot 2H_4O$/ Cupric Chromate	---	---	0.1 mg/m^3 (all chromates)	Not Listed.	---	---
Cutter, Cable M-1	---	B	7	N/A	Explosive C.	Variable	See package notes, bill of lading or labels.
Cutter, Reefing line	---	B, E, N	1	N/A	Explosive C.	Variable	See package notes, bill of lading or labels.
Cyclonite (RDX)	(See Cyclotrimethylene Trinitramine)	---	---	---	---	---	---

Table 3-1 (Continued)

Solid Propellant, Explosives, and Propellant Ingredient Characteristics[1]
(Summary for Fire Protection Guidance and Related General Information)

Propellant or Item	Formula/Synonym[2]	Storage Compatibility Group[3]	Explosives Hazard Class[4]	Toxicity TLV/EEL[5]	DoT Classification and Shipping Label[6, 7]	Explosion and Fire Hazards[1]	Fire Control Methods and Measures[2, 8]
Cyclotetramethylene Tetranitramine[1]	$C_4H_8N_8O_8$/Beta HMX; white crystals	M (Wet) L (Dry)	7 7	Non-Toxic	Wet - Explosive A. Dry - Not permitted to be shipped.	Dry HMX creates an electrostatic hazard. More powerful than TNT.	Do not fight an HMX fire, evacuate personnel. Should not be handled dry; where possible should be diluted with a solvent such as acetone. Use grounded equipment to transfer.
Cyclotol	(See Composition B)	---	---	---	---	---	---
Cyclotrimethylene Trinitramine[1]	$C_3H_6N_6O_6$/Cyclonite, RDX; white crystals	M (Wet) L (Dry)	7 7	N/A, inhalation causes intoxication progressing to seizures.	Explosive A. Shipped wet with water/isopropanol.	Dry RDX is highly sensitive to shock, friction and static electricity. It is about 1-1/2 times as powerful as TNT. Can hold a large electrostatic charge.	Do not fight an RDX fire; evacuate personnel. Whenever possible it should be handled when wet with water/isoproponal antifreeze solution.
DEGN	(See Diethylene Glycol Dinitrate)	---	---	---	---	---	---
DELTA HMX	(See Cyclotetramethylene Tetranitramine)	---	---	---	---	---	---
Destructor, HE M 10	---	B	7	N/A	Explosive A.	---	Do not fight a fire involving Destructors; evacuate personnel.
Detonating Cord	Chemical Formula/ Primacord	I	7	N/A	Explosive C.	---	---
Dicyclopentadienyliron[1]	$C_{10}H_{10}Fe$/Ferrocene; orange crystals	N/A	N/A	None recommended	Not listed.	When exposed to fire, emits toxic fumes. Moderate fire hazard.	Insoluble in water. Fire fighter should wear self-contained breathing apparatus.
Diethylene Clycol Dinitrate[1]	$C_4H_8N_2O_7$/DEGN; colorless liquid, freezes at 2°C.	N/A	7	N/A	Special Instruction - See DoT Title 49 CFR 173.51d.	Severe explosion hazard; will explode when exposed to shock. Dif. to ign	Do not fight fires involving DEGN; evacuate personnel

Dinitroglycol	(See Diethylene Clycol Dinitrate)	---	---	---	---	---	---
2, 4 Dinitro-toluene[1]	$C_7H_6N_2O_4$/Dinitrotoluol, DNT; yellow crystals	D	2 when exposed to fire, Class 7 when exposed to strong shock.	1.5 mg/m^3	Not regulated for land transport. Coast Guard regulates as combustible liquid. (IATA requires Poison label)	Moderate fire hazard and explosion hazard. May be an explosion hazard when involved in fire. Can be detonated by a very strong initiator.	Can be extinguished by use of dry chemicals, water, and CO_2. Fight fire remotely if large mass is involved.
Dinitrotoluol	(See 2, 4 Dinitrotoluene)	---	---	---	---	---	---
Diphenyl Guanidine[1]	$NHC(C_6H_5NH)_2$	---	---	Skin, eye irritant; caustic in water solution.	Not listed.	When heated to decomposition, it gives off toxic fumes.	Use water. wear self-contained breathing apparatus.
DNT	(See 2, 4-Dinitrololuene)	---	---	---	---	---	---
EC Powder	Nitrocellulose, 80%; remainder Barium and Potassium Nitrates.	J	7	N/A established	Explosive A.	Extreme fire hazard, explosion hazard.	Do not fight EC Powder fire; evacuate personnel.
EDNA	$C_2H_6N_4O_4$/Haleite; white powder, ingredient of Ednatol.	---	---	---	---	---	---
Ednatol	Haleite (EDNA), 55%; TNT, 45% yellow cast charge.	I	7	N/A	Explosive A.	Fire and explosion hazard. Severe fragment hazard in usual packages (shells or metal cases)	Do not fight fires involving packaged Ednatol; evacuate personnel.
Emite	---	O	7	N/A	Explosive A.	---	---
Ethyl Acrylate[1]	$CH_2CHCOOC_2H_5$/Ethyl propenoate; colorless liquid.	N/A	N/A	100 mg/m^3	Flammable liquid, Red label	Vapors when confined will explode. Fire and explosion hazard.	Foam, dry chemicals, or CO_2 may be used.
Explosive D	$C_6H_6N_4O_7$/Ammonium Picrate, Dunnite.	I	7	N/A	Explosive A.	Extreme fire hazard, relatively insensitive to shock, but will mass detonate when exposed to severe shock.	Use water.

Table 3-1 (Continued)

Solid Propellant, Explosives, and Propellant Ingredient Characteristics[1]
(Summary for Fire Protection Guidance and Related General Information)

Propellant or Item	Formula/Synonym[2]	Storage Compatibility Group[3]	Explosives Hazard Class[4]	Toxicity TLV/EEL[5]	DoT Classification and Shipping Label[6,7]	Explosion and Fire Hazards[1]	Fire Control Methods and Measures[2,8]
Ferrocene[1]	(See Dicyclopentadienyliron)	---	---	---	---	---	---
Firing Devices	Variable	B, E, N	1	N/A	Explosive C.	Fire hazard.	See package notes, bill of lading or labels.
Fuse	Variable	B, E, N	1	N/A	Explosive C. (See DoT Title 49 CFR 172.5)	Fire hazard.	See package notes, bill of lading or labels.
Fuses	Variable	B	3 or 7	N/A	Explosive A or C. (See DoT Title 49 CFR 172.5)	---	---
Fuses with boosters attached	Variable	B	7	N/A	Explosive A.	---	---
Fuses chemically actuated, containing ampoules which may initiate directly or indirectly, explosives, and explosive loaded components which are assembled in the conventional manner to form the finished explosive fuse.		A	7	N/A	---	---	---
Gamma HMX	(See Cyclotetramethylene Tetranitramine)	---	---	---	---	---	---
Glyceryl Nitrate	(See Nitroglycerin)	---	---	---	---	---	---
HMX, wet	(See Cyclotetramethylene Tetranitramine)	---	---	---	---	---	---
HMX, dry	(See Cyclotetramethylene Tetranitramine)	---	---	---	---	---	---
Hasethrol	(See Pentaerythritol Tetranitrate)	---	---	---	---	---	---
Igniters, rocket motor, Class B	Variable	B	3	N/A	Explosive B. Red label for railway express.	Variable	See package notes, bill of lading or labels.

Igniter Electric	Variable	B	3	N/A	Explosive C	Variable	See package notes, bill of lading, or labels.
Igniter Electric (M29)	---	O	7	N/A	Explosive A.	Fire hazard.	See package notes, bill of lading, or labels.
Lead Azide[1] (Wet)	N_6Pb/Azide; white-buff color aggregate.	M (Wet)	7	0.2 mg/m^3	Explosive A, (wet).	Explosive hazard severe, primary explosive, sensitive to heat, friction and shock when dry.	Do not fight Lead Azide fire, evacuate personnel.
Lead Styphnate (Wet)	$C_6H(NO_2)_3(O_2Pb)$/Lead Trinitroresorcinate; orange red-brown crystal.	M	7	0.2 mg/m^3	Explosive A, (wet).	Explosive hazard severe, primary explosive, sensitive to heat, friction and shock when dry.	Do not fight Lead Styphnate fire, evacuate personnel.
Magnesium Powder	Mg	C	1	Not established.	F. S. Yellow label.	Dangerous fire hazard. Moderate explosive hazard.	Use special extinguishers, G-1 powder, or MET-L-X.
MAPO[1]	$N(CH2)_3CH$ P:O/Tris 1-(2-methyl) aziridinyl phosphine oxide.	Not established.	Not established.	Not established.	Corrosive liquid white label.	Emits highly toxic fumes when exposed to heat-flame.	Miscible with water.
Mercury fulminate, (wet)[1]	$C_2N_2O_2Hg$ white to gray crystals.	M (Wet)	7	0.01 mg/m^3 (organic mercury)	Explosive A, (wet). Dry - not permitted.	Highly explosive, very sensitive to impact and friction. Primary explosive.	Do not fight fire; evacuate personnel. Wet with water.
Methyl Acrylate[1]	$CH_2CH_8OCH_3$	Not established.	Not established.	35 mg/m^3	Flammable liquid, Red label.	Explosion and fire hazard. Flammable limits 2.8 to 2.5 percent. Container may rupture at elevated temperature due to polymerization reaction and heat.	Foam, dry chemicals, CO_2. Cool containers with water to prevent polymerization.
Metriol Trinitrate[1]	$C_5H_9N_3O_9$/MTN, Trimethylolethane trinitrate	Not established.	Not established.	Not established.	Explosive A, special permit only.	Extreme fire hazard, will burn without detonating when unconfined in small quantities.	Do not fight MTR fire; evacuate personnel.
Military Pyrotechnics	Variable	N	2 or 7	Variable	Explosive, Classes A, B or C.	Variable	See package notes, bill of lading and labels.

Table 3-1 (Continued)

Solid Propellant, Explosives, and Propellant Ingredient Characteristics[1]
(Summary for Fire Protection Guidance and Related General Information)

Propellant or Item	Formula/Synonym[2]	Storage Compatibility Group[3]	Explosives Hazard Class[4]	Toxicity TLV/EEL[5]	DoT Classification and Shipping Label[6,7]	Explosion and Fire Hazards[1]	Fire Control Methods and Measures[2,8]
MTN	(See Metriol Trinitrate)	---	---	---	---	---	---
Nitramine	(See Tetryl)	---	---	---	---	---	---
Nitrates (inorganic, except ammonium nitrate)	Variable	K	1	Not established.	Oxidizing materials, N. O. S. Yellow Label.	Contributes to a fire's intensity in presence of a fuel.	Separate from fuels. Use water if a fire involves nitrates.
Nitrocellulose[1]	$[(C_6H_{10-x}O_{5-x}(NO_2)]n$ where x = number of NO_2 groups dependent upon degree of polymerization, n/NC; cotton-like fibrous solid or white powder when cut up.	M (when wet)	2 (wet)	N/A	Explosive A. Shipped wet - classification depends on wetting agent. Flammable liquid, Red Label. Flammable solid, Yellow label.	Highly dangerous fire hazard, when wet with solvent (alcohol) less hazard when wet with water. Explosive hazard when dry.	Copious amounts of water or foam applied remotely; evacuate personnel.
Nitroglycerin[1]	$C_3H_5N_3O_9$/NG; colorless, oily liquid	I	7	0.2 ppm inhalation causes intoxication, headache	---	Very severe explosion hazard; material has a low auto-ignition temperature, 180°C.	Do not fight NG fire; evacuate personnel. *NG* detonates at 222°C (5 seconds).
Nitroguanidine[1]	$CH_4H_4O_2$/Picrite; colorless pressed solid	I	7	Unknown	Explosive A.	Dangerous fire hazard; severe explosion hazard.	Do not fight Nitroguanidine fire; evacuate personnel.
Nitrostarch	$C_{12}H_{12}(NO_2)_8O_{10}$/Starch Nitrate	I	7	N/A	Explosive A.	Dangerous fire hazard; severe explosion hazard.	Do not fight Nitrostarch fire; evacuate personnel. Remotely wet with water to reduce involvement.
Norway Saltpeter	(See Ammonium nitrate)	---	---	---	---	---	---
Octol	HMX, 70%; TNT, 30% Buff colored cast expl.	I	7	N/A	Explosive A.	Explosion and fire hazard.	Do not fight Octol fire; evacuate personnel, apply water remotely.

P:O Tris 1-(2 methyl) Aziredinyl Phosphine oxide	(See MAPO)	---	---	---	---	---	---
PBX	RDX, 90%; Polystyrene, 8.5%; Dioctylphthalate, 1.5%.	I	7	N/A	Explosive A.	Explosion and fire hazard.	Do not fight PBX fire; evacuate personnel.
Pentaerythritol tetranitrate	$C_5H_8N_4O_{12}$/PETN, Penthrite, Hasethrol, Pentrin; white to light gray crystals	M	F	N/A	Explosive A.	Severe explosion hazard, on decomposing it emits highly toxic fumes.	Do not fight a PETN fire; evacuate personnel.
Penthrite	(See Pentaerythritol tetranitrate)	---	---	---	---	---	---
Pentolite	PETN, 50%; TNT, 50% to 10%; TNT, 90%/---; yellow-white cast	I	7	N/A	Explosive A.	Severe explosion hazard, on decomposing it emits highly toxic fumes.	Do not fight a PETN fire; evacuate personnel.
Perchlorates	Variable	K	1	N/A	Oxidizing Material N.O.S. Yellow Label	Moderate fire and explosion	Water and foam may be used to dilute and isolate from fuels in fire.
Percussion elements	Variable	P	7	N/A	Explosion C. No label prescribed.	---	---
Peroxide, inorganic	Variable	K	1	Variable	Oxidizing Material N.O.S. Yellow Label	Moderate fire and explosion hazard.	Water is the best control agent.
Peroxide, organic	Variable	---	---	N/A	Oxidizing Material N.O.S. Yellow Label	Dangerous fire; Severe explosion hazard.	---
PETN wet	(See Pentaerythritol)	M	7	---	---	Severe explosion hazard.	---
Petrin	(See Pentaerythritol tetranitrate)	---	---	---	---	---	---
Photoflash Powder	Variable	A	7	N/A	Explosive B, Red Class B label for express shipments.	Extreme fire hazard.	---
Picratol	Explosive D, 52%; TNT, 48%	I	7	N/A	Explosive B, Red Class B label for express shipments.	---	---

Table 3-1 (Continued)

Solid Propellant, Explosives, and Propellant Ingredient Characteristics[1]
(Summary for Fire Protection Guidance and Related General Information)

Propellant or Item	Formula/Synonym[2]	Storage Compatibility Group[3]	Explosives Hazard Class[4]	Toxicity TLV/EEL[5]	DoT Classification and Shipping Label[6,7]	Explosion and Fire Hazards[1]	Fire Control Methods and Measures[2,8]
Picrite Acid	$C_6H_2OH(NO_2)_3$/	I	7	0.1 mg/m^3	Explosive B, Red Class B label for express shipments.	Dangerous explosion and fire hazard.	Use water.
Picrite	(See Nitroguanidine)	---	---	---	---	---	---
Plasticol Nitrocellulose[1]	Varies from $C_{12}H_{17}(ONO_2)_3O_7$ $C_{12}H_{14}(ONO_2)_6O_4$/PNC	M (wet)	2	N/A	Explosive A.	Dry PNC is very sensitive to friction, heat, and spark. See also nitrocellulose.	Do not fight PNC fire, except by remote means with water; evacuate personnel.
Potassium Chlorate[1]	$KClO_3$/ ; transparent crystal to white powder	K	1 to class 2 if not in original shipping container	N/A	Oxidizing Material, Yellow Label.	Explosion hazard when mixed with organic or other readily oxidized material.	Fight fire involving chlorate with large amounts of water.
Primer detonators	Variable	B	3	N/A	Explosive A.	---	---
Primer electric	Variable	P	7	N/A	Explosive A & C.	---	---
Primers for small arms Ammunition	Variable	P	7	N/A	Explosive C. No label prescribed.	---	---
Pyrotechnic	Variable	A, C, K	1, 2 or 7	N/A	Explosive B, Red Class B for water and express shipments.	---	---
RDX	(See Cyclotrimethylene trinitramine)	---	---	---	---	---	---
Resorcinol[1]	$C_6H_4(OH)_2$/meta dihycloroxy benzene	N/A	7	N/A	Not regulated.	Fire hazard slight.	---
Rocket, catapult MK-1	Variable	B, E, N	3	N/A	Unknown	---	---

Rocket Heads HE "D" Loaded	Variable	A	5	N/A	Explosive A.	---	---
Rocket Heads HE "except pentolite and D loaded"	Variable	F	5 & 7	N/A	Explosive A.	---	---
Rocket Heads and Rocket pentolite loaded	Variable	A	7	N/A	Explosive A.	---	---
Rocket Motors (exclusive of heads)	Variable	F	2 or 7	N/A	Explosives A or B. Red Class B label for express shipment	---	---
Rockets practice	Variable	F	2, 4, or 7	N/A	Explosives A or B. Red Class B label for express shipment.	---	---
Shaped Charges	Variable	I	7	N/A	Explosive A.	---	---
Simulators M110, M117, M118, and M119	Variable	N	2	N/A	Not established.	---	---
Simulators M115 and SM142	Variable	O	7	N/A	Not established.	---	---
Simulator M116	Variable	B, Q	3	N/A	Not established.	---	---
Squibs, commercial	Variable	B, E, N	1	N/A	Explosive C. No label prescribed.	Fire hazard.	---
Sulfur[1]	S_8/Brimstone, flowers of Sulphur; yellow powder	N/A	N/A	15 mg/m^3 as dust, nuisance	Not listed.	Slight fire hazard, dust causes explosion hazard, toxic and irritating fumes produced during combustion.	Use water to cool below combustion temperature. Protect fire fighting personnel from fumes.
TEGDN	(See Triethyleneglycol Dinitrate[1])	---	---	---	---	---	---
Tetracene	$C_{18}H_{12}$/Naphthacene	I	7	Unknown	Explosive A.	Moderate explosion.	---
Tetranitor-Carbazole	$(NO_2)_4(C_6H_2)_2NH$/TNC	I	7	Highly toxic but no limit established.	Explosive A.	Fire and explosion hazard. Toxic fumes released during heating.	Do not fight TNC fires; Evacuate personnel.

Table 3-1 (Continued)

Solid Propellant, Explosives, and Propellant Ingredient Characteristics[1]
(Summary for Fire Protection Guidance and Related General Information)

Propellant or Item	Formula/Synonym[2]	Storage Compatibility Group[3]	Explosives Hazard Class[4]	Toxicity TLV/EEL[5]	DoT Classification and Shipping Label[6,7]	Explosion and Fire Hazards[1]	Fire Control Methods and Measures[2, 8]
Tetryl[1]	$C_7H_5N_5O_8$/ Trinitrophenylmethylnitramine, Tetralite, nitramine; light yellow crystalline form.	L	7	1.5 mg/m^3	Explosive A.	More sensitive to shock and friction than TNT. Explodes in 5 sec. at 257°C.	Do not fight Tetryl fires; evacuate personnel.
Tetrytol	Tetry, 65% to 75%; TNT, 35% to 25%/ ; light yellow to buff color.	I	7	N/A	Explosive A.	See tetryl and TNT.	Do not fight tetrytol fires; evacuate personnel.
TMETN	(See Metriol Trinitrate)	---	---	---	---	---	---
TNC	(See Tetranitrocarbazole)	---	---	---	---	---	---
TNT	(See Trinitrotoluene)	---	---	---	---	---	---
Tolite	(See Trinitrotoluene)	---	---	---	---	---	---
Torpex	RDX, 52%; TNT, 40%; Al, 18%/ ; gray where cast	I	7	N/A	Explosive A.	---	---
Triethyleneglycol Dinitrate[1]	$O_2NOCH_2CH_2OCH_2CH_2OCH_2CH_2OHO_2$/TEGDN	N/A	Not yet established use Class 7.	Not established, suggest 0.2 ppm by analogy with DEGN.	Explosive A.	Moderate fire hazard. Can be explosion hazard by regions shock, local heating to 220°C.	Use dry chemical or CO_2 agent, remotely applied if possible.
Trilite	(See Trinitrotoluene)	---	---	---	---	---	---
Trimetholoethane trinitrate	(See Metriol trinitrate)	---	---	---	---	---	---
Trinitrotoluene	$C_7H_5N_3O_6$/TNT, Tolite, Trilite, Tritol, Triton; light yellow crystalline form.	I	7	1.5 mg/m^3, skin warning	Explosive A.	High explosive and fire hazard. Strong shock will cause detonation. Explodes in 5 sec. at 475°C. Least sensitive of the military explosives.	Fight TNT fire remotely; evacuate personnel.

Tritol	(See Trinitrotoluene)	---	---	---	---	---	---
Tritonal	TNT/Al	I	7	N/A	Explosive A.	Similar to TNT, Al increases blast effect.	Fight Tritonal fire remotely; evacuate personnel.
Trotyl	(See Trinitrotoluene)	---	---	---	---	---	---
Zirconium[1]	Zr	C	1	5 mg/m^3 dust, 15 mg/m^3 nuisance level.	Flammable solid, yellow label. Shipped under water, or blanket with argon, helium.	Dangerous fire and explosion hazard when distributed in air. Explosion range in air 45 to 300 mg/1. H_2 gas envolved inpresence of water. Can burn in atmosphere of nitrogen or CO_2.	Use special mixtures of dry chemical, salt or dry sand. Powder containing 5 to 15% water burns more violently than dry powder.

[1]The information contained in this table is only useful for *general guidelines*; the reader is urged to consult the detailed information presented in Vol. II of this work for specific solid propellants and propellant ingredients. In addition to the indicated fire and explosion hazards, most of the tabulated materials also introduce a toxicity hazard when exposed to any heat and flame environment.

[2]Dangerous Properties of Industrial Material, 2nd Ed., 1963, Sax, N. Irving, Reinhold Publishing Corp., New York, New York.

[3]*Storage Compatibility Group* taken from DoD 4145.26M, paragraph 1105 and AMCP 706-117.

[4]DoD 4145.26M and 4145.27M (paragraph 8-7).

[5]American Conference of Government Industrial Hygienists.

[6]Department of Transportation, Hazardous Materials Regulations - Title 49CFR Parts 170-190. See specific exemption.

[7]There is no prescribed label for Class A Explosives; however, placarding is required. Class A explosives are not permitted for commercial air shipments. There is no prescribed label for Class C Explosives and placarding is not required.

[8]Fire Prevention Handbook, 12th Ed., 1962., National Fire Protection Association, Boston, Mass.

[9]Encyclopedia of Explosives and Related Items, Feroroff, Basil T., Picatinny Arsenal, Dover, New Jersey.

[10]Aluminum hydride should be stored in dry inert atmosphere. Should not be stored with oxidizers.

Table 3-2

Liquid Propellant and Propellant Ingredient Characteristics[1]
(Summary for Fire Protection Guidance and Related General Information)

Propellant or Item	Formula/Synonym[2]	Storage Compatibility Group[3]	Explosives Hazard Class[4]	Toxicity TLV//EEL[5]	DoT Classification and Shipping Label[6,7]	Explosion and Fire Hazards[1]	Fire Control Methods and Measures[2,7]
Alcohols:							
a) Methyl	CH_3OH/Methanol, wood alcohol (clear liquid	C	I	260 mg/m^3 (200 ppm)	Flammable liquid, Red Label.	Alcohols have wide flammable and explosive ranges. They burn with an almost invisible flame and may continue burning even after dilution to 20% alcohol (vol.) content with water. Stable liquids with flash point . . . (a) = 60°F, (b) and (c) = 70°F, (d) = 167°F.	Use fluidized bicarbonate-based powders, alcohol resistant foams, CO_2, water fog or water deluge for fighting fires. Water dilution of at least 5 to 1 suggested for prevention of re-ignition and flash-back.
b) Ethyl	C_2H_5OH/Ethanol, Type III A Alcohol, grain alcohol (clear liquid)	C	I	1900 mg/m^3 (1000 ppm)	Flammable liquid, Red Label.		
c) Isopropyl	C_3H_7OH/Isopropanol, rubbinb alcohol (clear liquid)	C	I	980 mg/m^3 (400 ppm)	Flammable liquid, Red Label.		
d) Furfuryl	C_5H_5OOH/furfurol (clear, straw colored liquid)	C	I	200 mg/m^3 (50 ppm)	Flammable liquid, Red Label.		
Ammonia, Anhydrous, liquid, or gas	NH_3/Refrigerant Ammonia (colorless, low boiling liquid)	C	I	35 mg/m^3 (50 ppm)// 10 min: 350 mg/m^3 30 min: 210 mg/m^3 60 min: 210 mg/m^3	Nonflammable gas, Green Label.	Flammability is limited; 16–25% (vol.) can be ignited by a heat source at 1200°F or higher.	Water fog or spray recommend for vapor control and fire extinquishment. Vapor is very soluble in water and copious application is recommended for a fire incident.
Aniline	$C_6H_5NH_2$/Aniline oil (colorless to straw colored, oily liquid)	C	I	19 mg/m^3 (5 ppm) Skin warning//no formal recommendations.	Poison B, Poison Label.	Moderate fire hazard, forms hot zones in storage tank fires. Stable liquid with flash point of 168°F.	Use foam, fluidized bicarbonate powders, water fog or CO_2 to fight aniline fire. Apply cooling water uniformly to storage tanks, motor cars, or drums involved in a fire. Dike unburned aniline and firefighting agents for controlled disposal.

Boranes:							
a) Diborane	B_2H_6/Boro-ethane, diboron hexahydride (low boilding liquid)	D	III	0.1 mg/m^3 (0.1 ppm)// 10 min: 10 ppm 30 min: 5 ppm 60 min: 2 ppm	Not classified, product identification and caution notices included on label.	Extreme fire hazard, usually ignites spontaneously upon release to air at temperatures above 20°C (68°F). Delayed ignition and flashback is significant explosion hazard since heat of reaction with air or absorption can ignite.	Control fire with area-wide water fog. Do not attempt to extinguish a large fire; this is very difficult and the residual diborane and partially reacted products are difficult to cope with safely.
b) Pentaborane	B_5H_9/Pentaborane-9 Pentaboron, ennahydride, (clear, colorless liquid)	D	III	0.01 mg/m^3 (0.005 ppm)//	Flammable liquid, Red Label.	Extreme fire hazard, usually ignites spontaneously upon release to air. Delayed reaction and reignition very likely to enhance explosion hazard if any ignition source is present.	Control fire with alcohol-resistant foam, followed with water deluge at conclusion of fire. Complete extinguishment is difficult. Bicarbonate-based powders, CO_2 effective only on small fires to completely cover fire zone. Do not use halogenated, e.g., CCl_4 or Halon 1301, agents.
Ethylene Oxide	C_2H_4O/ETO, (colorless liquid)	D	III	90 mg/m^3 (50 ppm)// 10 min: 650 ppm 30 min: 400 ppm 60 min: 250 ppm	Flammable liquid, Red Label.	Fire hazard severe, Explosive range 2-100 vol. % in air. Flash point -40°F (-40°C). Unstable liquid (monopropellant) in the presence of heat and can undergo autocatalytic polymerization and decomposition in the presence of alkali metal hydroxides, acids, the anhydrous chlorides of Fe, Mg, Sn, and Al or the oxides of Al and Fe (rust).	For fires involving small quantities of ETO use bicarbonate-based powder extinguishers, CO_2, or copious amounts of water. For large fires control fire with water fog, water spray, or alcohol resistant foam; extinguish with dry powder or alcohol foam and then follow by water dilution with at least 22 volumes of water per volume, prevent reignition or flashback.

Table 3-2 (Continued)

Liquid Propellant and Propellant Ingredient Characteristics[1]
(Summary for Fire Protection Guidance and Related General Information)

Propellant or Item	Formula/Synonym[2]	Storage Compatibility Group[3]	Explosives Hazard Class[4]	Toxicity TLV//EEL[5]	DoT Classification and Shipping Label[6,7]	Explosion and Fire Hazards[1]	Fire Control Methods and Measures[2,7]
Fluorine and Fluorine-Oxygen	F_2 and F_2-O_2(FLOX) yellowish gas or amber liquid bluish gray liquid as oxygen content is increased	A	II	0.2 mg/m^3 (0.1 ppm)// 10 min: 15 ppm 30 min: 10 ppm 60 min: 5 ppm	Flammable gas, Red Label as gas; special permit required for liquid shipment.	Fluorine initiates vigorous combustion spontaneously when in contact with flammables and with most materials including water and common sand. Delay autoignition is a definite hazard with those few materials having some resistance to fluorine oxidation.	Extinguishment of a fuel- and fluorine-fed fire is not possible. Evacuate personnel and control fire zone by application of water fog or fine spray to promote smooth burning of any spilled fluorine. The remote application of water is recommended; the fire control and cleanup personnel present must wear self-contained or air-supplied breathing apparatus as the combustion products are usually toxic. Dike firefighting and decontamination water for controlled disposal.
Halogen Fluorides							
a) Bromine pentafluoride	BrF_5/BPF	A	II	(0.1 ppm)// 10 min: 3 ppm 30 min: 1.5 ppm 60 min: 0.5 ppm	Corrosive, White Label; oxidizer.	The halogen fluorides initiate vigorous combustion spontaneously with most fuels. May react with water explosively in liquid-liquid pool combination and a delayed reaction is possible. As pure compounds they are stable to 600°F and nonflammable. Perchloryl fluoride is hypergolic with	Extinguishment of a fuel and halogen fluoride fed fire is not possible until the fuel is consumed. Water applied remotely as a fog or fine spray will promote smooth combustion of the halogen fluoride in a large spill. Bicarbonate-base powders may be used in small fires but bulk application of water or powder extinguishment agent will promote an explosive reaction with the pool mass of a large spill. Fire control and cleanup personnel must wear self-
b) Chlorine trifluoride	ClF_3/CTF	A	II	0.4 mg/m^3,C (0.1 ppm)// 10 min: 7 ppm 30 min: 3 ppm 60 min: 1 ppm	Corrosive, White Label; oxidizer.		

c) Chlorine pentafluoride	ClF_5/CPF	A	II	------, ---H 10 min: 3 ppm 30 min: 1.5 ppm 60 min: 0.5 ppm	Corrosive, White Label, oxidizer .	some fuels, is less reactive than the three halogen fluorides.	contained or air-supplied breathing apparatus for any of the pure compounds or their combustion products. Dike firefighting and decontaminating water for controlled disposal.
d) Perchloryl fluoride	ClO_3F/PF	A	II	3.5 mg/m^3, (3 ppm)// 10 min: 50 ppm 30 min: 20 ppm 60 min: 10 ppm	Non-flammable, Green Label.		

and responsiveness of all personnel whose responsibilities and job assignments are likely to take them into hazardous areas. Management should develop and implement a program which stresses the fact that all personnel are responsible for efforts which will result in the prevention of fires or the minimization of fire damage.

3-7.1.2 Policy. A policy statement in sufficient detail to identify responsibilities of each organization, and individuals, should be available for the guidance of managers.

3-7.1.3 Planning. A complete hazards analysis should be developed for each facility and operation during the planning phases.

3-7.1.4 Training. A formal training program should be developed for all personnel who are assigned to work in hazardous areas. This training should include fire prevention and fire fighting techniques appropriate to the hazards involved. The program should be periodically reviewed, updated as necessary, and approved by safety, fire prevention and other management officials.

3-7.1.5 Contingency Plans. Contingency plans should be developed and form a part of appropriate operating procedures.

3-7.1.6 Inspections. A system of periodic inspections should be implemented to assure good housekeeping, and continuous assessment of new or changing conditions and operations in each area and operation. These inspections should include the evaluation of operations and procedures, a check for incompatible materials and possible sources of ignition.

3-7.2 OPERATIONS. All procedures for operational areas should be carefully evaluated. Operating procedures associated with operations where there are specific fire hazards should be identified and contingency procedures should be developed.

3-7.2.1 Handling. Precautionary instructions should be available to each person required to handle hazardous materials and to respective supervisors and operating managers.

3-7.2.2 Transportation. Movement of hazardous materials should be preplanned to minimize probability of fire and to limit exposure of personnel and equipment not essential to actual transport of the propellant. (Reference 16).

3-7.2.3 Storage. One of the primary considerations in storing propellants should be limitation of fire areas. When stocks of important or critical items in storage so warrant, damage control can be enhanced by dividing the stock and storing portions in spearate repositories (assure that other combustibles are not left between storage facilities) or fire divisions. (Reference 13) Hazardous occupancies involving the storage of combustible materials should be effectively separated from other property and other occupancies to reduce potential loss and prevent propagation.

3-7.2.4 Manufacture. Each manufacturing process, in-process movement, and storage of hazardous materials should be analyzed for fire hazards. Appropriate fire prevention, protection and limitation measures should be compiled, published and made available for use by personnel, supervision, and management associated with manufacturing operations.

3-7.2.5 Use. Throughout all activities in which propellants or propellant ingredients are used, motion of personnel, materials, and equipment is an inherent part of the operation, thus providing possible sources of ignition. Risks to personnel, property and equipment can be reduced by: initiating measures to prevent static electricity; keeping quantities involved to a minimum; following procedures which will prevent unwanted or premature reactions; and assuring that equipment is properly designed and maintained.

3-7.2.6 Disposal. Collection and disposal of hazardous waste material should be a deliberate consideration during the planning of an operation. Schedules for removal should be frequent to prevent the accumulation of hazardous waste. See Chapter 4 for detail guidance of disposal of waste materials.

3-7.2.7 Vegetation Control. A vegetation control plan will minimize the danger of forest and grass fires. It will also prevent the spread of fire to and from adjacent (unmowed or uncontrolled) land. Vegetation control methods include: cutting, plowing, grazing, covering with noncombustible materials, utilization of nonflammable vegetation eradicators and seeding controlled areas with plant species that do not become fire hazards.

3-7.3 PREVENTION MEASURES. The fire prevention measures required for each operation must be established individually. However, there are general considerations that always apply. These considerations include but are not limited to the following:

a. Open fires and flames should be prohibited.

b. "No Smoking" areas should be established by operating officials with the concurrence of the Safety Engineer/Fire Chief. Adequate ash trays and Safety Engineer approved heating units for lights, cigars and cigarettes.

c. All electrical installations should be in accordance with the National Electric Code. No changes in electrical installation or wiring should be made except by, or with the approval of, the facility engineering or maintenance organization responsible for electrical installations. Electrical installations should be approved by the Safety Engineer.

d. Good housekeeping must prevail in all areas. A system of scheduled cleanups in accordance with a SAFE operating procedure approved by the Safety Engineer/Officer should be established.

e. All liquids should be stored in containers approved by the Safety Engineer/Officer.

f. Welding, cutting and burning will be done in propellant operation areas only when a hazardous operation permit has been issued.

g. Fire extinguishers shall be installed in accordance with the provisions of the National Fire Code (NFPA).

h. Fire prevention inspections by the Fire Marshal should be continuous.

i. Fire and emergency evaluation drills should be scheduled periodically. The frequency of these drills should be determined by the Safety Engineer/Officer and Fire Marshal.

3-7.4 FIRE PROTECTION. As used in this chapter "fire protection" refers to fire detection devices, fire fighting forces, and fire fighting techniques, its equipment and operations.

3-7.4.1 Detection Devices. Operating buildings should be equipped with flame or fire detection devices which will actuate fire alarms and suppression extinguishing systems. Temperature change, rate-of-rise photoelectric (Reference 14), pneumatic tube, or other types of devices are used in various occupancies. Considerations for selection include such aspects as; (a) reaction time required, (b) safety in hazardous locations and (c) ease of maintenance. Hand-actuated devices should be installed near operating stations and building exits. Communication of alarms to endangered personnel and to fire fighting units should be perfected by training and practice. Operating tests of alarm devices to prove their working effectiveness should be conducted at regularly scheduled intervals.

3-7.4.2 Fire Fighting Forces. An organized, adequately equipped fire fighting force should be available when hazardous conditions exist or potentially hazardous operations are in progress. The fire fighting force should be thoroughly trained in the specific fire and explosion hazards of each hazardous material, methods of fighting each type of fire, use of personnel protective clothing and equipment, applicable safety precautions, and fire inspection procedures. Fire drills should be conducted to insure that all personnel are familiar with procedures and fire fighting equipment.

3-7.4.2.1 Public Fire Department. Neighboring public fire departments should be kept informed of potential fire and explosion risks within the plant. When possible agreements should be negotiated with neighboring municipalities and corporations which provide for mutual aid in the event of an emergency.

3-7.4.2.2 Fire Wardens and Emergency Crews. Fire wardens and emergency crews should be appointed for each area and trained in "first aid" and fire fighting procedures appropriate to the hazard(s) to be encountered. Emphasis should be placed on selection of fire wardens and emergency crews from among those personnel who are most likely to be in the immediate vicinity in case of fire, rather than from those whose duties may require their absence for extended periods of time. At least three levels of succession should be provided for.

3-7.4.3 Fire Fighting Techniques. Although water is the most universally applicable fire fighting agent, there are important exceptions to its use in extinguishing special types of fires, as discussed in the individual chapters of this manual. These exceptions relate to fires involving fluorine, chlorine trifluoride and such molten metals as sodium, potassium, etc. In addition, water is to be used on metal hydrides and magnesium only when the advantage to be gained, for example, the cooling of adjacent combustibles, outweighs the effects of the reaction. Special classes of liquid propellant fires are discussed in the pertinent chapters of the manual. The following discussion is concerned with conventional fire fighting materials and methods.

3-7.4.3.1 Terminology.

a. Heat wave. In storage tanks containing low burning volatile liquid fuels whose boiling point is over 200°F, a heat wave may be formed when the fuel temperature rises nearly to the boiling point to a depth increasing with the length of the burning time. The movement of the boundary between the heated and unheated zones is called a heat wave.

b. Hot zone former. In the process of burning, blends of moderately volatile petroleum fuels lose their more volatile components in the heated zone (see heat wave) with a rise in the temperature of the residual components to considerable above the initial boiling point of the original blend (e.g., 200°F to 400°F). Crude oil, for example, is a hot zone former.

c. Slop-over. When the heat wave or hot zone in a storage tank in which liquid fuel is burning drops to a water pad in the tank or when water is applied to the hot zone's surface, a violent "stream distillation" of water and fuel occurs, causing the liquid to froth and slop over from the tank. The extent of the slop-over depends on the temperature and depth of the heated zone.

d. Spontaneous heating. Spontaneous heating is a result of low energy combustion in which the energy required for initiation is associated with normal atmospheric temperatures.

e. Spontaneous ignition. Spontaneous ignition means the initiation of flame type combustion as the result of a temperature rise associated with spontaneous heating.

3-7.4.3.2 Classification of Fires.

a. Class A (combustibles). Combustibles in class A are solid materials such as wood, paper, cardboard (i.e., cellulosic in nature), and coal which go through a "hot-ember" stage of combustion, that is, they produce glowing embers and char or coke. In the initial combustion stages of these materials, the gases are driven off or liberated by heating. In attempting to extinguish fires of these materials in inaccessible spaces, however, one must always bear in mind the possibility of a slow, smoldering-ember type of combustion.

b. Class B (combustibles). Combustibles in class B are liquids which must vaporize before combustion can take place. For example, a pool fire of gasoline actually involves the vapors above the pool, which are replenished by fresh vapors issuing from the liquid's surface. In extinguishing fires of this type of combustile, all sources of ignition must be suppressed to prevent the fuel vapors from being rekindled.

c. Class C (combustion). Class C combustion denotes the presence of an actual or potential electrical hazard in connection with combustibles of class A or B. This category defines the situation in which a water stream, foam stream or any other electrically conductive material must not be used for fire fighting because it would pose an extreme hazard primarily to personnel and secondarily to electrical equipment.

d. Class D (combustibles). Combustibles in class D include magnesium and other metals, including lithium and sodium, whose combustion temperature and combustion produced heat are high in comparison with those of wood. In general, water stream should not be applied to fires of this type because of the hazard of explosive spattering.

e. Mixed classes of combustion. This term may be used to describe combustion involving two or more of the four classes identified.

f. Flare combustion. Flare combustion is defined as a fire which is supported by a physical mixture (or chemical compound) comprising both fuel and oxidizing components and, in consequence, does not depend on atmospheric oxygen for support. Examples of flare type combustibles are solid propellants, explosives such as TNT, and mixtures of fuels and oxidizers such as JP-4 and fuming nitric acid.

g. Hypergolic combustion. This term may be used to designate the special combustion reaction between two hypergols or a hypergolic mixture of fuel and oxidizer, that is, the type of combustion that is initiated spontaneously following the mixture of fuel and oxidizer. The combustion of a mixture of aniline and fuming nitric acid is an example of this type.

3-7.4.3.3 Fire Fighting Agents. Water is not used on class C fires except when applied as water fog from a well grounded fog nozzle. (This technique, however, should not be used by personnel untrained in its application). Though water fog may be used in fighting class B fires, foam (a water-base agent) is generally preferred because it minimizes the chance of the flame's flashing back. Antifreeze and "loaded-stream" water solutions are used particularly for fighting class A fires. Other types of fire extinguishing agents may be grouped as shown in Table 3-3.

a. Water with no additives. The application of water depends on the specific circumstances of the fire. Where range is required a straight stream is used; or two or more impinging jets may be used to provide a water spray at an extended distance from the hose nozzles. Water fog is highly effective in controlling and extinguishing fires, but it must be applied at close range. For fires of volatile hydrocarbon and other water-insoluble fuels, water fog must be used with care because of the danger of flashback which, however, is less critical with respect to fuels whose flash point is higher than 100°F.

b. Wetting agents. These are sometimes used with fog on class B fires, since they will promote some emulsification on the fuel's surface. As they will break down protein-base foam, however, they must not be used in combination with foam or in tanks supplying water from which foam may be made.

c. Water with salt additives. Calcium chloride is used as an antifreeze for water to about -40°F. For lower temperatures, lithium chloride or a lithium/calcium chloride salt mixture may be used. In these winterized solutions, the solids content ranges over 30 percent by weight. In making up solutions, one should refer to pertinent technical data and should take care to compensate for using the proper crystalline form of the salt; that is, if any anhydrous salt is specified, the use of a hydrated salt without correcting for the water of hydration, will result in an insufficient salt concentration in the solution. These winterized water solutions should not be used on nitric acid, chlorine trifluoride and fluorine, for gaseous products of a corrosive nature will be generated. It is recommended that the use of antifreeze water charges be limited to units for which stock-issue formulations are available. These prepackaged salts, which are designed for making up specific charges, contain the proper amount of corrosion inhibitor (usually sodium chromate) required to prevent damage to the extinguisher from internal corrosion.

Loaded stream extinguisher charges are marketed commercially. The type of salt used is potassium carbonate with inhibitor. The encrustation of salt on embers in the burning materials impedes the penetration of oxygen and thus achieves a more presistent extinguishing effect. The use of a salt in concentrated solution, however, reduces the weight of water present in a given charge; since water is actually the most effective extinguishing component, the general use of loaded stream extinguishment "across the board" is not recommended. Using loaded stream on nitric acid, chlorine trifluoride, etc., is not advisable, because heat and gas will be generated in the reaction, though in the case of nitric acid the gas will be carbon dioxide.

d. Water as foam. "Mechanical foam" is the term used to designate a dispersion of air in a solution of water and foam liquid concentrate; it is also called "air foam" or simply "foam." "Chemical foam" is generated by chemical action and the liberation of carbon dioxide between acid salts, $Al_2(SO_4)_3$, and bicarbonates, $NaHCO_3$, in the presence of foam stabilizers; these are not now used as extensively as mechanical foams.

Foam extinguishes liquid fuel fires by cooling the surface of the liquid and forming a blanketing barrier to the fuel vapors, sealing off the fuel from the ambient air. Since foam reacts with hot fuels essentially in the same way as water, it will react similarly if applied to a burning fuel tank in which a "heat wave" has developed; that is, there is danger that the burning fuel will either slop or "boil" over.

e. Mechanical foam. Mechanical foam is prepared by first mixing the foam liquid concentrate and water to make up a solution varying from 3 to 6 percent of the concentrate in water; the resultant solution is then mixed with air under conditions of high turbulence to generate the foam. The military foam liquid concentrate JAN-C-266[1] (or OF-00555) is intended for use in a 6 percent concentration. The ratio of air to water solution in mechanical foams depends on the type of equipment used to generate the foam. For liquid

Table 3-3

Fire Extinguishing Agents

Water-base Agents	Vaporizing Agents	Dry Agents	Special Agents
No additives present: fog straight stream pattern spray	Carbon dioxide (CO_2)	Sodium bicarbonate or bicarbonate of soda ($NaHCO_3$) with fluidizing and moisture-repelling additives in standard and foam-compatible formulations.	Mixtures of organic liquids, or powders and liquids, particularly for metal fires.
Wetting agents (additives reducing surface tension) present: Advantageous in very specialized fires, such as cotton bales, fabrics, etc.	Carbon tetrachloride (CCl_4) - obsolete type	Potassium bicarbonate ($KHCO_3$) with fluidizing and moisture-repelling additives.	
Salt additives present: straight (loaded) stream straight stream antifreeze	Bromochloromethane or monobromochloromethane (CH_2ClBr)	Monoammonium dihydrogen phosphate $(NH_4) H_2PO_4$ types in the form of free flowing powder that has a sealing and slightly intumescent reaction on hot surfaces, excluding air from the surface of solid fuels.	
Foam liquid additives present: straight stream foam foam pattern spray	Bromotrifluoromethane or Monobromotrifluoromethane (CF_3Br)	Powders for extinguishing metal (class D) fires.	
	Bromochlorodifluoromethane or monobromomonochlorodifluoromethane (CF_2ClBr)	Dry dirt and sand.	

fuel surface fires, particularly in tanks and diked areas, a ratio of 3/1 is generally preferred. In aircraft-crash rescue operations, ratios from 5/1 to 11/1 are used.

Foam may be produced by means of a special train of pumps (generally of the positive-displacement type) which proportion the concentrate in water, then add air to the solution, and mix by beating them together, a process called pressure foam generation. In other instances, water and concentrate may be premixed by an auxiliary proportioning pump, or proportioned at the time the water is pumped, and then fed to an aspirating type nozzle or an in-line aspirating type foam generator which mixes air and solution. The operation of these devices depends on solution pressure. Foam nozzles with a built in aspirating type proportioner and a pickup tube for aspirating foam liquid concentrate directly from the shipping can are also available. Foam nozzles produce foam with air-to-solution ratios of 5/1 to 9/1, in either straight stream or spray patterns. For alcohol-fuel fires, a foam liquid concentrate is available but foam generation with this concentrate must immediately follow mixing with water.

The quality of mechanical foam is described by two characteristics: (1) expansion ratio, which is the total fluid volume of foam (including air and liquids) produced by a unit volume of foam solution, and (2) quarter drainage time, which is the time required for one-fourth of the foam solution to drain from a standard sample of foam, determined in standardized apparatus. For liquid-petroleum-fuel surface fires, the desirable characteristics for mechanical foam are an expansion ratio of 4 and a quarter drainage time of 4 minutes.

For tanks containing fuel oil or other heavy distillates of low volatility, mechanical foam may be applied at a rate of about 0.2 gpm per square foot of burning fuel surface by base injection through the product line. This method is not recommended for fuels whose flash point is below normal room temperature (69°F), since fuel drops are entrained in the foam as it rises to the fuel surface; while imbedded in the foam surface, these drops continue to emit combustible vapors, burn and accelerate foam breakdown. For gasoline and volatile fuels, a foam application rate of 0.4 to 0.5 gpm per square foot of burning surface is recommended. A given rate of foam application will enable the control of a greater fire area in liquid-fuel-spill fires than in deep pool fires, since surface fire may be progressively extinguished. For the spill type fire, spray foam is particularly effective.

f. Chemical foam. Chemical foam is prepared by mixing granulated powders with water. In fighting fuel storage fires, the powders are added to water flowing in feed lines by hoppers that feed them to the throat of a venturi. In the 2-component system, the "acid" powder is added to one water stream and the bicarbonate to another; then the two solutions are brought together by a "Y", at which point generation of foam begins. In the single-component system, a mixture of "acid" powder, bicarbonate powder and the foam-bubble-stablizing ingredients is fed to a single hopper unit, at which point foam is generated. Since a chemical reaction controls the temperature of foam generation, length of piping and water flow rate are critical factors in the generation of satisfactory foam. Thus, chemical foam systems must be carefully laid out and are not very flexible in operation. If the water temperature drops below 45°F, the solution of the powders and the and the chemical reaction may become too slow for satisfactory foam generation. Chemical foam is stiffer and drains out less rapidly than mechanical foam. Fixed applicators are generally used.

g. Carbon dioxide. Carbon dioxide is an extinguishing medium of low toxicity which acts for the most part as an oxygen diluent and blanketing agent. Discharge from the extinguisher, the liquefied carbon dioxide is vaporized and transformed in part into a "snow." Its effectiveness, however, is essentially the same as at normal room temperature, since the contents are cooled below 87.5°F during discharge and snow is formed in the discharge stream. Carbon dioxide is not as effective as some of the halogenated liquids, and it must be applied with care to guard against back-flashing. It is used on class B and class C fires.

h. Carbon tetrachloride. Because significant toxic hazards are associated with carbon tetrachloride, and in view of its relatively low effectiveness, it is being replaced by other extinguishing agents, i.e., carbon dioxide, monobromotrifluoromethane, and powder-base agents.

i. Bromochloromethane. Bromochloromethane, also known as chlorobromomethane, is a halogenated liquid which is more effective and less toxic than carbon tetrachloride; in addition, it does not generate significant quantities of phosgene when applied to fire. It is subject to autoignition at temperatures of about 1000°F, but this property does not detract from the effectiveness of this agent in open fuel fires. The use of aluminum in continuous contact with bromochloromethane must be avoided. Since bromochloromethane is a more effective solvent than carbon tetrachloride, gasket materials satisfactory for use with carbon tetrachloride may not perform satisfactorily with it. Like other halogenated liquids, bromochloromethane suppresses a flame by chemical means.

j. Bromotrifluoromethane. Bromotrifluoromethane is available in the 2.75 extinguishers, which are similar in operation to the 2.5 and 5 pound carbon dioxide extinguishers. Bromotrifluoromethane is less toxic than CO_2, although in the presence of fire it produces hydrogen fluoride. Tests have shown, however, that the pyrolysis products of bromotrifluoromethane are much less toxic than those of carbon tetrachloride or bromochloromethane. In confined spaces and with high humidity, hydrogen fluoride may etch or "fog" glass. To recharge the bromotrifluoromethane extinguisher requires special equipment, one reason being that the internal pressure is boosted with dry air or nitrogen to give a total of about 400 psi at 70°F. Bromotrifluoromethane is a highly effective fire extinguishing material.

k. Bromochlorodifluoromethane. Bromochlorodifluoromethane is similar to bromotrifluoromethane, but its boiling point is higher, approximately 21°F.

l. Sodium bicarbonate. Sodium bicarbonate base powder is one of the principle dry agents whose particles are about 20 microns in size. These agents are compounded as a finely pulverized powder to promote ease of flowing and resistance to moisture. These agents, with fluidizing additives, are very effective against liquid fuel spill fires, particularly if there are no obstacles in the spill area. The extinguishing action of the powders, in comparison with that of halogenated liquids (which are chemical agents) may be largely physical. As the material in a powder extinguisher tends to "pack" after long standing and may not be fully discharged when needed, it is advisable before using the extinguisher, to turn it over and set it upright to agitate and loosen the contents. Powder agents must be used with care to prevent back-flashing. They are less effective than vaporizing liquids in fighting class A fires and, when solid combustibles are involved, are not recommended for class C fires. (As a group, vaporizing liquids also are not recommended for use in combating class A fires, but they are used for class C fires). Standard formulations of the fluidized powders are destructive to protein-base foams; but "foam-compatible" formulations are available. Though the use of sodium-bicarbonate-base powders on electrical fires presents no hazard to the operator of the extinguisher, the powder at flame temperatures becomes electrically conductive; thus, the use of this agent on fires involving live electrical circuits is not recommended if suitable vaporizing agents are available.

m. Potassium bicarbonate. Physically, the potassium-bicarbonate-base Purple K powder is like the sodium-bicarbonate-base type, except that the formulation is colored light purple in accordance with the military specification. The particles may be finer than those of most sodium-bicarbonate-base powders, but the greater effectiveness of the potassium bicarbonate agent is believed to result from the potassium ion formed when the powder is applied in a flame zone. The radiation flash when the powder is applied to fire is less noticeable with potassium bicarbonate than with sodium bicarbonate.

n. Monoammonium dihydrogen phosphate. When heated to flame temperatures, these powders coat solid surfaces with a tight, slightly intumescent coating which excludes air. They are less resistant to the effects of moisture than bicarbonates and present a more difficult clean up problem after the fire has been attacked or put out. They are rated for extinguishing class A as well as class B fires and are effective on small metal fires. They would not be effective on propellant or explosive fires.

o. Powders for extinguishing Class D fires. Powders for extinguishing class D (metal) fires (Met-L-X), chloride salts (G-1), eutectic chlorides, etc., are available commercially. These are specialized formulations and are not recommended for other classes of fires.

p. Fluorospar-type agent. A mixture of 70 percent powdered fluorospar and 30 percent sodium-bicarbonate-base powder, expelled from a suitable container with nitrogen or carbon dioxide gas, has been found useful in controlling small chlorine trifluoride fires.

3-8 POST ACCIDENT/FIRE/EXPLOSION ACTION

3-8.1 SUPERVISOR.

a. Insure that medical assistance is provided to all injured persons.

b. Notify all interested parties.

c. Take immediate action to minimize the expansion of the accident, fire or explosion.

d. Secure all areas to prevent entry by unauthorized personnel.

e. Make notes on the specific location of all personnel and material involved.

f. Investigate all accidents/fires/explosions and property damage.

3-8.2 HIGHER ECHELON SUPERVISION (above first level supervision).

a. Insure that supervision is instructed in the emergency action plan.

b. Review all investigation reports to determine what can be accomplished to minimize the possibility of recurrence.

c. Utilize the professional services of the Safety Engineer/Officer and Fire Chief to investigate accidents.

d. Follow up to insure timely submission of all reports.

3-8.3 SAFETY ENGINEER/OFFICER.

a. Provide staff supervision and coordination of all accident/fire/explosion investigation and reporting.

b. Receive, review and maintain a file of all reports of accidents, fires and explosions.

c. Analyze accident reports for the purpose of developing cause factors and make recommendations for corrective action.

3-8.4 CONTRACTING OFFICER. Coordinate with the Safety Engineer/Officer regarding reporting of accidents, fires, and explosions in accordnance with the terms of contracts and local, state, and federal health and safety laws, ordinances, codes and regulations.

3-9 SPECIAL PROBLEMS AND THEIR TREATMENTS

References 15, 16, 17, 18, and 19 and the bibliographic entries in the appendix deal with problems of special interest. These references should be reviewed before work is begun with these specific fuels.

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CHAPTER 4

DISPOSAL AND DECONTAMINATION

4-1 INTRODUCTION

4-1.1 GENERAL. Liquid-propellant fuels and oxidizers and solid propellants are highly reactive. Consequently the propellants and their products possess certain hazardous properties which must be fully understood by all who are required to handle them. It is not within the scope of this chapter to outline complete disposal techniques for all propellants, but rather to outline general principles for the decontamination and disposal phases of propellant handling. The principles set forth here should not be regarded as inflexible; for, where special conditions exist, special procedures may need to be devised with the advice of qualified personnel.

The principal hazards to be dealt with in operations involving liquid propellant disposal and decontamination are: fire, explosion, fragmentation, toxicity, and cryogenic temperatures.

4-1.1.1 Fire. The disposal area must be kept free of extraneous combustible materials.

4-1.1.2 Explosion and Fragmentation. The principles guiding the elimination and control of fire hazards are generally applicable to explosion hazards. Where applicable, barricades should be provided to protect personnel from the effects of an explosion. It is essential to locate the disposal area far enough from other facilities, buildings, and boundaries so as not to present a danger. See Bibliography in section 4-7.

4-1.1.3 Toxicity. Poisoning can occur in several ways: by inhalation, ingestion, and skin contact. A single incident of exposure may not cause symptoms of poisoning; dosages may be cumulative and result in eventual occurrence of symptoms. It is essential to consider disposal operations in light of the Clean Air and Clean Water Acts, as well as to afford on-site protection for personnel.

As a general guide to the control of toxic vapors, gases, mists, and dusts, hygienic standards such as threshold limit values, often referred to as TLV's are useful. Refer to specific liquid propellants in Vol. III and solid ingredients in Vol. II, and to Chapter 1 of this volume.

4-1.1.4 Cryogenic Liquids. Cryogenic liquids (liquefied gases) present hazards because of their low temperatures. Contact between flesh and a liquid or metal at a cryogenic temperature will result in almost instantaneous freezing. If skin touches metal at these low temperatures, it will freeze and may adhere to the metal. Prolonged exposure may embrittle body flesh and fingers and hands, with possibility of their cracking and breaking. The destruction of skin and muscle tissue will be similar to that caused by third degree burns. A pool of cryogenic liquid held in direct contact with the skin will raise a blister similar to that of a severe or second degree burn. This is due to temperature alone and will occur even when the liquid is non-corrosive.

Toxic cryogenic liquids are especially hazardous since they may not only cause free burns, but also can enter the body through the wounds produced if toxic reaction products are allowed to remain at the site, thus complicating the severity of the problem.

4-1.2 ACCIDENT PREVENTION REQUIREMENTS AND CONSIDERATIONS. Listed herein are accident prevention requirements which should be considered by those responsible for or engaged in propellant disposal and decontamination.

a. Permit only trained and authorized personnel to conduct disposal and decontamination operations.

b. Disposal and decontamination operations should be performed by the minimum number of persons needed to accomplish the task, but never by one person alone. There should always be someone at a safe distance, ready to render aid.

c. Personnel responsible for, or involved in, the disposal or decontamination of hazardous materials must be cognizant of the materials' characteristics, and hazards. They must be informed of correct disposal methods, accident prevention measures, and emergency and first aid procedures.

d. Clothing and respiratory equipment suitable for the chemical or propellant being disposed of must be worn. Protective clothing, tools, and other equipment must be decontaminated before reuse. Items must be cleaned as soon as possible with prescribed decontamination agents.

e. Disposal or decontamination areas must not be entered by unprotected personnel until the areas have been determined to be safe and those areas should be decontaminated on a regular bases.

f. Advance notice of disposal and decontamination operations must be given groups such as the fire department, medical department, safety department, and other activities that could be affected.

g. Areas where disposal and decontamination operations are conducted should have warning signs posted.

h. Water and air pollution must be avoided.

i. Limits must be established as to the amount of material which may undergo disposal or decontamination at one time.

j. Smoking and eating in disposal and decontamination areas must be prohibited. In addition to the obvious fire hazard, the handling of food and tobacco often furnishes a means of entry of poisonous materials into the body.

k. Health standards should be set by cognizant medical authority.

l. To assure the removal of hazardous chemicals that may have come into contact with the body, operators should bathe and thoroughly scrub immediately after leaving the diposal and decontamination area wherever feasible. A complete change to fresh clothing may be necessary. Specific procedures must be developed for safe and effective handling of contaminated clothing.

4-1.3 PERSONNEL TRAINING. Persons involved in propellant disposal and decontamination operations need to be instructed in the following subjects:

a. The nature and hazards of the material

b. Location, use, and care of all personal protective equipment

c. Course of action to be taken in case of leaks or spills

d. Housekeeping and hygienic practices

e. Compatibility of materials and other chemicals with the propellant

f. Safe handling methods

g. Self-aid and first-aid.

4-2 SITE SELECTION

The site selected for disposal and decontamination shall be located at the maximum practicable distance from all magazines, inhabited buildings, buildings, public highways, railways, and operating buildings. (See Bibliography in Section 4-7.) Sites must also be located in relation to the direction of prevailing winds, to prevent the spread of fire and hazardous concentrations of toxicants. Where possible, natural barricades shall be utilized between the site and operating buildings or magazines. When destroying material by burning, the possibility that the material may detonate must be recognized and appropriate protective barriers or distance separation shall be utilized for the protection of personnel and property.

Dry grass, leaves, and other extraneous combustible materials shall be removed within a radius of 200 feet from the disposal and decontamination site. The grounds shall be of well packed earth and shall be free from large stones and deep cracks in which explosives might lodge. Explosive materials shall not be burned or detonated on concrete mats.

Fire-fighting equipment shall be readily available to extinguish brush or grass fires, and, if necessary to wet down the ground between burnings and at the close of each day's operations. Ordinary combustible rubbish should be destroyed at a location removed from places where propellants are destroyed.

4-3 DISPOSAL METHODS

The method selected for disposal of any propellant must depend upon the characteristics of the particular propellant in question. In all cases, however, the method used should be the one which presents the least hazard to personnel and property and produces a minimum of pollution. Consideration must be given to pollution control in all disposal and decontamination operations.

Insofar as the obligation of rocket propulsion test and launch facilities to maintain air and water quality is concerned, the following apply: the Federal Water Pollution Control Act, as amended, (33 USC 466 et seq.) and Executive Order 11288; and the Air Quality Act, as amended (USC 1857) and Executive Order 11282. (See Section 1-4.5 and 1-4.6)

4-3.1 AMOUNT OF MATERIAL. The amount of material to be destroyed at one time shall be consistent with reasonable and safe operation. The maximum amount prescribed by applicable regulations shall not be exceeded. In the absence of established limits, the number of units that may be destroyed safely at one time shall be determined carefully by starting with a limited number and then gradually increasing that number until the maximum which can be destroyed without risks to life and property is determined. (See also Section 1-4.5 and 1-4.6 .) Only materials which are completely compatible will be mixed for disposal.

4-3.2 BURNING. One of the more common means of propellant disposal is by burning. This method may be used for both solid propellants and liquid fuels and oxidizers. It is easily accomplished in the case of fuels which may be burned in atmospheric oxygen. Oxidizers that are disposed of by burning are burned with an appropriate fuel as the reducing agent. Compliance with local air pollution ordinances and regulations will be mandatory.

A number of methods of burning are used; some are as follows:

4-3.2.1 Pan. A metal tray on which the propellants may be sprayed or poured at such a rate that the rate of burning equals the rate of flow of the fuel or oxidizer.

4-3.2.2 Pits. Deep depressions prepared in open ground.

4-3.2.3 Burn Pond. A shallow pit filled with water to a prescribed level which is used to dispose of large quantities of gaseous propellants. Flashback is prevented by bubbling the gas or liquid (if it floats on the surface) through the water and igniting it at the surface. Care must be taken to maintain the water level and ignite the material before large quantities of flammable gas accumulate.

4-3.2.4 Incineration. It may be necessary on some occasions or in some locales to dispose of propellants by burning in an incinerator in quantities that are small enough to be easily controlled while burning.

Incinerators shall be shut down and cooled thoroughly when it becomes necessary to remove accumulated residue. Repairs shall be made only during shutdown. If it is necessary for personnel to enter the incinerator for clean-out purposes, adequate respiratory protection should be provided to prevent inhalation of toxic dusts or fumes.

4-3.3 DETONATION. Some types of propellant may be disposed of by detonation. This method of disposal should be reserved, however, for only those propellants which cannot be readily disposed of by other means. Quantity-distance requirements must be observed (see Chapter 2).

4-3.4 DUMPING IN DEEP WATER. Explosive loaded ammunition and pyrotechnics may be dumped in water at least 3000 feet deep and at least 10 miles from shore; provided authority is granted by the responsible government agency. Material so dumped must have a minimum weight of 100 pounds per cubic foot to insure negative buoyancy (reference 1).

4-3.5 DILUTION WITH WATER. In many instances water is the most effective and readily available disposal and flushing agent. It should be noted, however, that water diluted propellants may still possess hazardous properties, i.e., alkalinity, acidity, volatility, flammability, etc., that may require further decontamination. A few propellants may react with water and form hazardous products.

4-3.6 DILUTION WITH AIR. In the case of some volatile propellants, disposal can best be accomplished by allowing the propellant to evaporate under atmospheric conditions. It is imperative that all personnel clear the area until the liquid has evaporated and the vapor concentration reached a level deemed safe.

4-3.7 NEUTRALIZATION. There exists a number of propellants which cannot be disposed of effectively by any of the aforementioned methods. These usually may be neutralized by reaction with another chemical agent and rendered safe. Before any type of neutralization procedure is initiated, a thorough knowledge of the chemical neutralizer, its concentration, method of distribution, the mechanism of the neutralization reaction, and possible hazards of and disposal of the neutralization product is necessary.

4-4 SOLID PROPELLANT DISPOSAL

4-4.1 PROPELLANT WASTE. Propellant wastes should be regarded as having sensitivity characteristics at least as hazardous as those of the propellants from which obtained. Waste collection and holding areas should conform to the propellant quantity/distance/barricade standards.

Experience has shown that propellant wastes which have been contaminated with foreign material - for example, floor sweepings, sand or dust from ground spillage, or residual material from uncleaned containers - are likely to be more sensitive than the propellants from which the waste is derived. From this, it follows that: (a) transfer of waste from one container to another should be avoided as much as possible; it is preferable to destroy the material in the container in which it was collected; (b) every effort should be made to avoid spillage or leakage which will result in contamination of the material with ground or floor dirt; and (c) when such spillage or leakage does occur, it should be quantitatively retrieved, and the mixture of waste and foreign material is to be handled as primary explosive, not as propellant.

4-4.1.1 Disposal of Specific Types of Propellant Waste. Methods for the disposal of various types of waste encountered in the manufacture and handling of solid propellants are detailed in Vol. II, Chapter 7.

4-5 LIQUID PROPELLANT DISPOSAL

Because of the great range of properties of liquid propellants, many different means are required to accomplish disposal. In Vol. III, the material for each specific propellant includes a section on the applicable disposal and decontamination methods, and the reader is referred to that volume for details.

4-6 REFERENCES

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CHAPTER 5

HAZARD IDENTIFICATION AND EVALUATION TECHNIQUES

5-1 INTRODUCTION

The hazards of rocket propulsion operations arise from some or all of the following factors:

a. Operating conditions: high pressures, rapid release of energy accompanied by flame and noise

b. Chemical reactivity: corrosive attack, catalytic or thermal decomposition

c. Toxicity

d. Potential for uncontrolled fire and explosion.

Two types of safety measures can be brought to bear against these hazards: preventive measures and monitoring functions. This chapter begins with a discussion of preventive steps, starting with a resume of the requirements for materials compatibility, cleanliness, and pressure-proofing of piping, motor cases, component parts, etc. Assuring the integrity of solid propellants by radiographic inspection, and the purity of liquid propellants and pressurizing gases by chemical analysis, are also positive steps in accident prevention and are discussed next. Meteorological forecasting and monitoring are also treated as preventive measures, because operations must sometimes be restricted to times when wind direction, wind velocity, and temperature-altitude profile are favorable for dispersion of toxic material and acoustic energy.

Safety monitoring is discussed next. Equipment must be provided for early detection of leaks and of fire so that timely steps can be taken to prevent the situation from getting out of hand. Furthermore, it is often advisable to monitor sound intensity, and also the vibrations of structures to be sure that they are not approaching dangerous levels.

Despite our best efforts to prevent them, accidents still occur, and the effects are not always what might have been anticipated. There is much to be learned from these events, especially the large ones that are too expensive to be deliberately staged. Therefore, the final part of the chapter discusses the evaluation of accidents. Types of instruments that will provide significant data on blast and thermal effects are described and are recommended for installation, particularly at large test and launch facilities. Toxic releases must also be evaluated by suitable devices to protect both on-site and off-site personnel. Finally, brief mention is made of the information that can be derived from the fragments produced by an accidental explosion.

5-2 PREVENTIVE MEASURES (Reference 1)

5-2.1 SYSTEMS. The design of aerospace ground and auxiliary equipment should not only consider their end purpose but also the preventive measures that can be taken to minimize operational hazards. It is mandatory that system safety measures be recognized from the time of system conception.

It is not the intent of the manual, nor would it be possible, to list all of the hazards that could be encountered. The purpose here is to outline a systems approach to design that incorporates preventive measures and briefly mentions or discusses some of the more common items to be considered.

5-2.2 SYSTEMS ENGINEERING SAFETY ANALYSIS. The complexity of present and proposed aerospace systems and the number of individuals and organizations involved in their development all tend to create system safety problems. Increasing acquisition costs and new management concepts are reducing the number of hardware changes available for incorporating recommended safety design changes. These factors require that a system safety approach be identified early in the development stage so that it may have some impact upon design requirements and trade-off decisions.

The necessity for safety analysis stems from the need to know whether a design is potentially capable of complying with a predetermined safety goal or requirement, or if design changes are necessary to meet these objectives.

Testing can be used to further develop designs or to verify the attainment of goals and requirements.

5-2.2.1 System/Subsystem Hazard Analysis. Hazard effect analysis is a qualitative technique used to assess the level of safety of interrelated activities which must be performed in a specified chronological order, within a given range of valves to an acceptable standard of safety. Its result documents the following:

a. A brief description of the function being analyzed

b. An appropriate classification of the hazard involved

c. A summary concerning the hazard effects

d. A summary of the recommended corrective action.

This analysis can be an effective and useful approach when used primarily to assess the safety posture and to document corrective actions that are planned divergencies from the normal operational mode.

5-2.2.2 Gross Hazard Analysis. This may be defined as a comprehensive, qualitative, non-mathematical assessment of the safety features of the end item. Areas to be considered include the following:

a. Isolation of energy sources

b. Fuels and propellants: their characteristics; hazard levels; handling; storage and transportation safety features; etc.

c. Proposed system environmental constraints

d. Use of explosive devices and their hazards classification

e. Compatibility of materials

f. Human factors

g. Effect of transient current and radio frequency energy

h. Use of pressure vessels and associated plumbing

i. Documentation concerning the safe operation and maintenance of the system

j. Training pertaining to safe operation and maintenance of the system.

These areas represent classifications of known precedent in accident causation that are intersystem by nature. The cumulative effects of deficiencies (or normal operation in some cases) in many parts of the aerospace systems are usually involved. Such deficiencies cannot be conveniently analyzed by the functional breakdown required in a failure mode and effects analysis as they do not lend themselves to a quantitative assessment of the hazard because of the number and characteristics of the variables involved, and the difficulties involved in obtaining quantitative data concerning the sequential events constituting the hazard.

5-2.2.3 Failure Mode and Effect Analysis. The purpose of this type of analysis is to avoid costly modifications by ferreting out latent design and operational deficiencies. The analysis consists of an independent critical review of the system, coupled with a systematic examination of all conceivable failures and an evaluation of the effects of these failures on the operational capability of the system.

5-2.2.4 Catastrophe Analysis. This is a qualitative safety review based upon the potential causative factors for the various catastrophic failure modes of the system. Examples of these failure modes are fire, explosion, implosion, and structural damage due to handling. This type of analysis should not be limited in concept and must include:

a. Catastrophic incidents under normal standby or normal operating conditions

b. Catastrophic incidents under abnormal conditions

c. Catastrophic incidents under emergency conditions.

5-2.2.5 Training. The extent of the training required to obtain a desired level of reliability is a function of the complexity of the task and the receptiveness of the individual to the training effort. Potential hazards can frequently be avoided by controlling the manner and sequence of systems operations. Procedures and checklists are essential in helping to perform this task.

5-2.2.6 Inspection Program. A safety inspection program can be employed as a means of resolving safety hazards—particularly those hazards that arise from carelessness, oversight, or familiarity. These conditions may exist in all phases of aerospace system life including design, production and operation. An effective safety inspection program must cover all three phases. Basically, the safety inspection is exposure and enforcement. Exposure is achieved through qualified systems safety engineers probing the design, production, and operation areas, and ensuring that identified hazards are corrected and that uncorrected hazards are identified. Enforcement is realized by the documentation of hazards, follow-up for resolution, and management support of the safety audit effort.

5-2.3 SERVICE, SUPPORT, AND AUXILIARY EQUIPMENT. The safe conduct of chemical rocket propulsion operations depends to a considerable extent upon the proper performance of a number of support systems and equipment. A general discussion of the safety criteria relevant to equipment design follows. These criteria are presented with the intent of aiding in eliminating potential hazards.

5-2.3.1 Fuel/Propellant Equipment. The highly reactive nature of propellant fuels and oxidizers requires that they be given special emphasis during system design and operation. Some of the safety considerations and criteria for ground fuel/propellant systems follow:

Select materials that are compatible with the service fluid

Ensure that insulation is nonabsorbent and cannot react chemically with service fluid

Use cleaning agents that will yield surfaces compatible with service fluid and level of cleanliness specified

Specify system component interchangeability

Separate storage areas, holding areas, plumbing, and vent systems sufficiently to prevent vapor or fluid mixing

Protect pressure vessels from exceeding structural limitations by relief devices

Ensure that primary relief devices are not obstructed

Design vent systems to safely dispose of hazardous vapors

Specify system contamination control

Use electrical equipment that is approved for operation with the service fluid

Protect all equipment from lightning and static electricity

Locate fixed storage vessels in accordance with AFM-127-100, Quantity-Distance Criteria (Appendix E, Liquid Propellant Handling, Storage and Transportation)

Locate a positive shutoff valve at the storage vessel outlet

Install storage vessels in a basin capable of containing the entire contents of the vessel plus 10%

Ensure that vent stacks from underground vessels are not hazardous to aircraft or personnel

Design mobile storage tanks to conform to DOT regulations

Route lines to minimize effects of leakage hazards

Design the system to have a minimum safety factor of 4:1

Design system piping for free expansion and contraction

Protect system from severe environmental conditions

Do not install piping near any ignition that can cause a fire due to leakage

Protect the system against damage by personnel or movable equipment

Provide pressure and fluid bleeders to isolate operating units

Design automatic valves to have manual bypass capabilities

Do not use components to support piping or vice versa

Provide adequate clearances for fireproofing, insulation and maintenance

Group pipelines that run in the same compass direction to minimize structural support requirements

Provide shutoff valves throughout the system for isolation purposes

Provide inspection and drainage openings throughout the system, including the lowest point

Identify the system as to fluid, pressure, direction of flow, capacity, and material

Properly anchor and support the system

Provide personnel protection barriers for personnel working in hazardous pressure areas

Provide positive pressure indicating devices at critical pressure or maintenance points

Keep fittings or connections to a minimum

Ensure that torque values are not reduced below the value that will prevent leakage in bolted flange fittings

Use fittings that will withstand entire system pressure including predicted surge pressures

Ensure that fittings will not separate sealing surfaces due to vibration

Use seals that are chemically compatible with service fluid and surrounding environment

Ensure that piping, tubing, or flexible hose does not have short radii bends

Provide system filtration at needed locations to protect critical components

Provide a visual means to detect filter effectiveness

Install relief devices wherever pressure buildup can cause a potential system hazard

Properly insulate and support cryogenic vessels

Provide positive visual pressure indicators on pressure vessels

Provide closed loop venting where toxic hazards exist

Ensure that transfer hose has a safety factor of 5:1

Include design features to prevent damage of seals

Avoid using fittings in inhabited areas

Ensure that the flow of service fluid can be stopped in the event of system malfunction

Provide service fluid drainage in the event of a leak, spill, or rupture

Design system routing to avoid inhabited areas

Protect electronic controls from arcing or short circuits

Ensure that pumps are compatible with the service fluid

5-2.3.2 Hydraulic Equipment. The extreme flexibility of fluid elements raises a number of safety problems. Special consideration must be given to structural configuration and the compatibility of the parts of the fluid. Some of the safety considerations and criteria for the development and selection of hydraulic components follow:

Provide specific design instructions for system proof check

Check all materials for fluid compatibility

Install a drain plug at the lowest point in the reservoir

Vent the reservoir in such a manner that it will not create a hazardous condition to personnel or equipment

Ensure that no possibility exists for interconnecting pressure and return systems

Provide a pressure regulator where a power pump is used

Design a component so that it cannot be installed incorrectly

Ensure that the downstream structural limits cannot be exceeded

Install a fluid level gage on the reservoir

Locate the reservoir where there is a free circulation of air

Install a positive pressure indicating device on the reservoir

Ensure that the system fluid requirements will not exceed two thirds the capacity of the reservoir

Ensure the pump is unloaded during the idle cycle

Provide a filter for the pump suction line

Ensure that the pump is driven by the proper rated horsepower

Design system routing to bypass inhabited areas or provide alternative protective measures

Design emergency systems to be completely independent of primary systems

Identify all piping in accordance with MIL-STD-1247 or local authority

Eliminate sharp corners to reduce installation damage

Use high pressure fittings with extra heavy or double heavy pipe

Ensure that the minimum bend radius is 2.5 to 3 times the inside diameter of the tubing

Provide sufficient tube and pipe supports

Provide airborne test connectors

Ensure that flexible hose has 5% to 8% of the total hose length allocated for slack

Protect all transfer lines from chafing

Specify the use of nonflammable hydraulic fluid

Provide backup rings where pressure can cause O-ring extrusion

Ensure that the filter does not create an excessive pressure drop

Design filter cases to the minimum system safety factor

Ensure that internal surfaces of component and tubing have rounded corners and do not invite fatigue failure

5-2.3.3 Pressurization and Pneumatic Equipment. The hazards of pressurized systems can be extreme. Sudden release of the stored energy of compressed gas can produce hazards ranging from explosive disintegration of the systems—with resultant high velocity fragments—missiles with rocket-like thrust. Safety criteria and considerations for design and operation of pressurization and pneumatic systems follow:

Provide system protection so that a regulator malfunction will not cause downstream system failure

Ensure that the system working pressure is not greater than 75% of the maximum regulator capacity

Ensure that regulator bypass capabilities to the downstream side do not exist where system downstream components will not meet full upstream pressure requirements

Locate a pressure readout device as close as practical to the pressure regulator

Ensure that relief valves will initially regulate system pressure no higher than 110% of working pressure

Specify pressure relief where source pressure can exceed the design levels of the system

Size relief valves to exceed the maximum flow capacity of the pressure source

Install relief ports so that escaping gases or vapors will not be hazardous to personnel or equipment

Ensure that shutoff valves are not used for maintenance purposes unless a burst disc or other positive relief device is installed in parallel

Provide devices for bleeding trapped gas from between components

Port safety relief valve outlets to atmosphere

Key or size adjacent incompatible system pressure connectors so that it is physically impossible to connect the wrong unit or pressure level

Identify all lines by contents, pressure, and direction of flow

Ensure that components and systems are qualified and acceptable for use in the intended environment

Provide flexible hose restraint that is 50% greater than maximum calculated open-line-force pressure of the hose

When using restraints for high pressure systems, the type and construction of the restraint used (sandbag strap, or other tie down) shall be adequate to protect against the maximum credible failure of the system.

Specify that pressure settings and safety factors are in accordance with prescribed procedures

Provide pressure readout to ensure that pressure is below hazard levels

Equip all direct pressure readout gages with shatterproof glass or plastic faces and blowout plugs

Perform proper proof checks as specified

Identify hand valves to indicate function and sequence of operation

Avoid routing gas systems through inhabited areas

Continuously ground piping and equipment to reduce triboelectric ignition potential (static or friction generated electricity)

Ensure that contaminants are not introduced into the system from improper use of materials or lubricants

Do not introduce inert gases into inhabited area

Ensure that lubricants and other materials are acceptable for use with the system gas

Ensure that storage pressure can be bled off to allow replacement of components

Provide reservoirs and storage vessels with shutoff valves for maintenance

Specify separate pressurization sources downstream of primary regulation when pressurizing noncompatible commodities

Ensure that selection of compressors has minimized explosion hazard

Provide protection where lines or components can be damaged

Locate check valves to prevent critical air loss

Ensure that provisions are made to prevent installation of components in reverse

Ensure that pressure reservoir type and temperature ratings are correct for the system working range

5-2.3.4 Electrical/Electronic Equipment. The design of electronic equipment and electrical systems must provide for the safety of personnel during installation, operation, and maintenance of all elements of the system. Further, the system itself must include design features which will eliminate or minimize equipment damage or malfunction during its service life. General safety design criteria and considerations for electrical/electronic equipment follow:

Select materials for electrical/electronic equipment in accordance with equipment specification or as specified in MIL-E-4158

Ensure that flammable materials are not specified for use in the system

Do not use glass fiber materials where they may cause skin irritation

Select materials that will not liberate gases or fumes which are toxic, corrosive, flammable, or explosive under any combination of specified service conditions

Do not use dissimilar metals in intimate contact unless suitable corrosion protection is provided

Use insulating and jacketing compounds in cordage and cabling that exhibit long life without degradation of performance under the anticipated service conditions

Derate power cordage and cable when operating at ambient temperatures that exceed 30°C

Hold wiring termination points to a minimum

Ensure that wiring terminals are sufficiently strong to support the wires attached and to endure necessary fabrication and maintenance operations

Select terminals that will not turn or loosen when subjected to certain service conditions

Provide adequate spacing or barriers to prevent corona breakdown or low-leakage resistance under specified service conditions

Ensure that the moisture-excluding property of potted parts is not degraded by normal soldering operations on terminals

Space terminals to which wires are soldered far enough apart so that work on one terminal does not damage another

To prevent accidental body contact, cover or protect high-voltage terminals located near components which are frequently worked on

Protect terminal points from shorting by eliminating foreign objects and debris, and from possible circuit degradation by reducing dirt, moisture, or other contaminants

Include assembly instructions in the design for connectors which require special tools or processes

Use crimp connections for connector termination where practicable

Provide alignment pins and keyway arrangements, or similar features on adjacent connectors to prevent cross-connection

Avoid connectors with unkeyed symmetrical pin arrangements

Furnish caps or covers to keep unmated connectors from contamination

Terminate connectors so that receptacle pins are "hot" and plug pins are "cold"

Ensure that layout and spacing of connectors permit ease of connection and disconnection when using appropriate tools

Furnish articles of equipment likely to require future additional circuits with connectors having spare contacts in accordance with MIL-STD-454

Identify equipment assemblies and parts in accordance with MIL-STD-130

Color code chassis wiring in accordance with MIL-STD-681

Ensure that all external equipment parts, excluding antenna and transmission line terminals, are at ground potential at all times

Do not use shields, excepting coaxial cables, as a current-carrying ground connection

On plug and convenience outlets for portable tools and equipment include provisions for automatically grounding the case of such equipment when the plug is mated to the receptacle

Ground inactive wires installed in long lines (conduit or cable) to allow for discharge of stray or static electricity

Specify that the ground connection to the chassis or frame provides a corrosion-resistant connection

Secure shielding adequately to prevent contact with exposed current-carrying parts

Terminate shielding a sufficient distance from exposed conductors to prevent shorting or arcing between the conductor and the shielding

Provide primary circuits and cables with overload devices to protect against damage by fire, explosion, or overheat due to electrical overload

Locate fuses at a convenient, serviceable point so they may be readily replaced

Provide blown-fuse indicators where practicable

Attach at least one spare fuse of each type and rating to applicable units of the set

Furnish fuses that can be replaced without the use of tools

Ensure that circuit breaker restoring features are readily accessible to the operator, and a visual indication is given when the breaker is tripped

Ascertain that normal performance characteristics of the source or load are not altered by the use of protective devices

Protect personnel from accidental contact with voltages exceeding 30 volts rms or DC while operating equipment

Protect personnel from voltage hazards by the use of electrical interlocks in accordance with MIL-STD-454

Provide grounding rods in all transmitting equipment of sufficient size to accommodate such a provision and where voltages are in excess of 70 volts rms

Provide ground studs to accommodate a portable grounding rod for transmitters of small physical size where voltages exceed 70 volts rms

Provide personnel barriers or guards on all contacts or terminals exhibiting voltages between 70 and 500 volts rms or DC with respect to ground

Mark clearly the voltage present on contacts and terminals exceeding 500 volts rms or DC

Furnish voltage dividers or other means to allow the safe measurement of potentials in excess of 1000 volts peak

Design equipment exhibiting a radiation hazard (e.g. microwave or X-ray) within the limits of MIL-R-9673

Provide high-voltage circuits and capacitors operating at more than 250 volts with reliable discharge features, unless the circuit or capacitor discharges to 30 volts or less within 2 sec of power removal

Ground or insulate controls, control shafts, knobs, or levers to prevent shock or burns to personnel

Ensure that the temperature of exposed parts and equipment enclosures which may be contacted by operating personnel does not exceed 60°C at an ambient temperature of 25°C (see DN 4E1, Para. 3.6.10, reference 1)

Ascertain that the temperature of front panels and operating controls does not exceed 43°C at an ambient temperature of 25°C (see DN 4E1, Para. 3.6.10, reference 1)

Guard or protect all moving mechanical parts such as gears, fans, and belts when the equipment is complete and operating

Avoid sharp projections, corners, or edges on cabinets, doors, hinged covers, and similar parts of equipment

Locate, recess, or guard critical switches, breakers, and similar controls in a manner to prevent accidental displacement or activation

Design mechanical linkage, instrument leads, and electrical connections to positively prevent inadvertent reversing or cross connection

Protect personnel from possible injury from implosion of cathode-ray tubes

In the event of meter failure, assure that meters possess overload bypass or alternate features to eliminate high-voltage potential at the meter terminals

Do not specify metal ladders for use around electrical/electronic equipment and facilities

Provide adequate equipment cooling for performance under any combination of service conditions

Locate or configurate ventilation holes so foreign object cannot be inserted inadvertently to contact high-voltage sources

Design equipment to withstand any probable combination of environmental conditions without mechanical or electrical malfunction

Use inherently safe (e.g. explosion proof, dustproof, moisture-proof) equipment in all hazardous environments

Provide proper equipment accesses to all points, units, and components which may require testing, adjustment, maintenance, or repair

Locate accesses away from dangerous mechanical or electrical components where possible; otherwise, placard such accesses as to the potential hazard

Furnish accesses with internal fillets, or with rubber, fiber, or plastic if they might injure the operator's hands or arms

Provide screwdriver guides on adjustment points which are located near high voltages

Position equipment components and wiring to prevent damage from opening and closing the assembly

Provide rests, stands, or other protectors to prevent damage to delicate parts when elements of the equipment are removed for repair

Ensure that units are small and light enough for one man to carry and handle, whenever this is feasible (see DN 4E2, SN 3.1(1) reference 1)

Provide convenient handles on units to assist in removal, replacement, or carrying

Provide guide pins on subassemblies for alignment during mounting

Furnish limit-stops (with overrides) on all rollout racks and drawers

Locate components so there is sufficient space to use test probes, soldering irons, and similar tools without difficulty

Locate tubes so they can be replaced without removing assemblies and subassemblies

Do not use resistors, capacitors, and wiring that interferes with tube replacement

Route cables so they cannot be pinched by doors, lids, or covers

Locate cables so they cannot be abraded, chafed, or used for handholds

Locate cables so they are not bent and unbent sharply when they are connected and disconnected

Provide delicate conductors such as wave guides and high-frequency cables with guards, protective routing, or similar protection

Incorporate fail-safe features into equipment designs and installations where the failure or malfunction of the equipment may injure the operator or damage the equipment or adjacent equipment

5-2.3.5 Transportation and Material Handling Equipment. The following criteria contain the mobility constraints that apply to the design of all transportation and handling equipments peculiar to aerospace ground systems. The listing does not attempt to encompass those safety regulations applicable to public utility carriers.

5-2.3.5.1 Slings (Ropes, Spreader Bars, Hooks, Rings, Shackles and Links).

Design lifting/hoisting slings for a specific operation. Provide all slings with rings, links, hooks, or eyes so they can be safely suspended from hooks

Where cable or rope slings are employed in conjunction with hoists or cranes, provide sling cables of sufficient length to ensure that the angle formed by the sling cables at the hoist attaching points does not exceed 45°

Design slings to meet specified proof load requirements

Specify that hooks for hoisting apparatus are to be fabricated from forged steel, wrought iron, or built-up steel plates. Ensure that hooks are fitted with safety latches, or other safety devices, and shaped to prevent loads from slipping off

Prohibit the use of open hooks on slings or any other equipment used in handling operations

Specify wire rope be made of corrosion resistant material when there is a possibility it will be used in a corrosive environment

Specify fiber rope of high-grade manila hemp with a minimum tensile strength of 11,400 psi

5-2.3.5.2 Trucks and Dollies.

Incorporate shock-mounting, nonresetting G-meters, dessicants, and other protective devices on trucks and dollies used for moving sensitive equipment

Provide positive cradling or support devices and tie-downs that conform to the shape, size, weight, and contour of the load to be transported

Provide grounding connections in the design of all trucks and dollies

Enclose all electric wiring in a chafe-resistant protective material and clamp clear of sharp edges and moving parts

Specify permanently attached safety chains for vehicles that must be towed with sufficient rated capacity to hold the truck or dolly to the tractor in the event of towbar failure or disconnection.

5-2.3.5.3 Auxiliary Equipment (Jacks, Tiedowns, Chocks and Towbars).

Design jacks with mechanical adjustable stops to ensure even lifting when several jacks are being used

Provide a mechanical safety locking device to prevent inadvertent lowering of the load in the event of a system failure

Specify tension and torque requirements for tie-down straps

Design wheel chocks to conform to the wheel size and load of the mobile handling equipment

Specify that towbars are fabricated from material of sufficient strength to resist permanent deformation under operating loads

Provide hinged-type towbars with a positive latch to hold the towbar in the raised position with a stop to prevent contact with the equipment

Provide grounding straps on all auxiliary equipment

5-2.3.5.4 Portable Shelters and Protective Covers.

Discourage the use of nonconductive materials in the design of shelters or protective covers that can generate or hold a static charge

Provide electrical bonding to maintain a uniform ground potential on separable sections of portable metal shelters that are separated by insulating or nonconductive materials

Ensure that portable shelters and protective covers are conspicuously marked for STEP, NO-STEP, HOISTING POINT, LIFTING POINT, CENTER OF GRAVITY, THIS SIDE UP, FOLD LINE, and other markings as required

5-2.3.5.5 Cranes, Derricks and Hoists.

Design electrical control, junction, and switch boxes to exclude the entry of water or other undesired and incompatible substances

Enclose all electrical controls, switches, and other sparking devices in a vapor-tight or explosion-proof enclosure when the equipment is intended for use in a corrosive or potentially explosive atmosphere. (Reference 2, National Electrical Code, Article 500.)

Provide separate and independent mechanical and electrical brakes for the lifting mechanisms on all electrically powered equipment

Design mobile equipment with grounding provisions that are readily accessible

Design permanent mechanical stops into the equipment to prevent operation in a dangerous mode or position

Incorporate an automatic braking or stop feature on the cable drum in the event of a power failure or mechanical failure in the hoisting mechanism

Design the cable length to permit at least four full wrappings around the drum when the equipment is at the maximum extended position

Specify spark arrestors for the exhausts of all engines on mobile equipment

Provide electrical bonding to maintain a uniform ground potential on all structural framework separated by insulating materials

Provide safety guards for critical or emergency controls and switches to prevent inadvertent operation

Provide a braking system capable of braking, lowering, and safely holding a minimum of 150% of rated load

Provide grounding in accordance with NECA Article 610, Para. (f), (reference 2)

5-2.3.5.6 Cradles (Jigs-Fixtures).

Mark guide lines on cradles designed to carry particular loads to match guide lines on equipment being carried. Locate guide lines to be visible after the equipment is loaded

Shape cradles to fit the equipment to be carried

Ensure that the cradle has sufficient bearing area to support the load when the equipment must remain on the cradle without supporting bands or hoists

Provide metal straps to attach the equipment to the cradle during positioning procedures. Equip restraining straps with quick-disconnect, easily accessible fasteners. Encase metal straps with nonabrading material to prevent damage to the equipment

5-2.3.5.7 Over-The-Road Trailers.

Provide shock mounting, nonresetting G-meters, desiccants, and other appropriate protective fixtures on transporters used for moving sensitive equipment

Provide positive cradling or support devices and tie-downs that conform to the shape, size, weight, and contour of the load to be transported

Include appropriate grounding provisions as required

Enclose all electrical wiring in protective material such as metal conduit to preclude damage resulting from sharp edges and foot traffic

Provide safety chains for vehicles that must be towed. These chains must have the capacity to hold the transporter to the prime mover in the event of a towbar failure or disconnection.

Provide adequate lighting for movement and maintenance during hours of darkness

Equip all transporters with a braking system that can be efficiently activated by two separate and independent power sources

Provide roll-on/roll-off transfer and handling systems to ensure that aerospace vehicle stages are subjected to a minimum of handling

5-2.3.5.8 Water Transporters (Barges and Vessels). (Reference 3)

Ensure that all openings in the shell, deck, inner bottom, deckhouses, and structural bulkheads are well-rounded, square-cornered cuts

Ensure that sharp and ragged edges of exposed structure, access holes, etc., are fitted with half-rounds, welded halved pipe, etc., over sharp corners for protection of personnel and equipment

Require adequate camber on all-weather decks

Ensure that decks are suitably reinforced at load points for deck, machinery, hatch covers, vehicle transporter tie-down fittings, etc.

Provide a means to prevent the anchor chain from being snared on the ship's structure. Where necessary use chafing plates, castings, or half-rounds to protect the structure from anchor chain whip.

Provide power-operated windscreen wipers on the pilot house with full and quarter speed regulation adjustable from the inside

Provide pipe guard rails or chain rails with portable stanchions around all hatches, escape manholes, and moving machinery

Ensure that the forecastle deck towing fittings are stiffened as required to resist loads resulting from maximum towing pull without injury to, or deformation of, the main hull structure

Provide tie-down fittings and supports on the main deck and in the cargo shed for securing the vehicle stages. Stiffen the hull structure as required to resist the loads that will be imposed on the tie-down fittings

Provide safety treads for inclined ladder treads, at the head and foot of all ladders, on both sides of entrance door coamings, and elsewhere as required to ensure safe footing

Provide for fire dampers as required by the U. S. Coast Guard regulations. Fit all dampers (including fire dampers) with an indicator, to show the position of the damper and combined adjusting and locking device, that is located to be easily accessible and visible

Require flume stabilization on ocean vessels to minimize acceleration imposed upon the aerospace vehicle stages

Equip barges and ocean vessels with hard covers that will afford protection for the stages during transit

Provide basic shop facilities on board vessels to permit emergency repairs to the tie-down system, transporter, or the vessel itself in the event of damage

5-2.3.5.9 Minimum Safety Factors and Proof Load Requirements for Handling Equipment. Ensure that proof load test requirements and minimum safety factors are specified that conform to SN 3 (1) in reference 1. If the manufacturer's specification or equipment warranty does not allow proof checks to the level specified in this Sub-Note, the equipment rated capacity must be lowered to a level which will permit an acceptable proof load.

5-3 INSPECTION AND SAMPLING TECHNIQUES

5-3.1 SOLID PROPELLANTS.

5-3.1.1 General. Numerous nondestructive testing methods are used to inspect solid rocket motors and components. Some of the more common techniques include borescopic, ultrasonic, penetrant, and radiographic inspection. With the exception of radiography, no undue hazards are presented by these methods; the procedures are straightforward and no further discussion is warranted in this volume. The remainder of this section will deal with the measures needed to cope with the inherent dangers of radiographic inspection.

5-3.1.2 Radiography. The use of radiation sources to perform radiographic inspection of rocket motors and components for detection of voids, separations, and other anomalies has become a standard practice in the propulsion industry. Each program requires that techniques be utilized to obtain specific information about various items that are essential to the specific program. Therefore, only general items that pertain to all operations are presented.

5-3.1.2.1 Policy. Radiographic operations will comply with all Federal and State requirements and regulations.

5-3.1.2.2 Definitions. The terminology is defined as follows:

a. Radiography: The examination of the structure of materials by nondestructive methods utilizing radiation

b. Radiographer: An individual who is responsible for operation of the radiographic facility in compliance with the policy

c. Radiographic Facility: Stated in 5-3 above—any room, enclosure, or operating area in which either a radiation machine or radioactive material is utilized for inspection. This will exclude medical X-ray, qualitative and quantitative analytical devices such as X-ray diffraction machines and electron microscopes.

5-3.1.2.3 Standards. The applicable standard practices are given in the following listing:

a. Radiographic exposure devices and storage containers for sealed sources will not have a radiation level in excess of an amount determined by the specific facility adhering to Federal and State regulations when the device is in the safe- or off-position.

b. Each radiographic exposure device will be provided with a lock or outer locked container designed to prevent unauthorized or accidental exposure. The device will be under the cognizance of the supervisory radiographer and will be kept locked at all times except when under the direct supervision of a radiographer.

c. Locked radiographic exposure devices and storage containers will be physically secured to prevent tampering or removal by unauthorized personnel.

d. Radiographic facilities of the radioisotope type (such as cobalt cameras) will require immediate area monitoring each time they are visited to assure that the shutters are in the off-position and that radiation levels are well within acceptable limits.

e. Prior to each radiographic exposure, the radiographer will inspect the radiographic facility to assure the absence of personnel.

f. Radiation signs and symbols required will be posed at each entrance to the radiographic facility.

g. Each radiographic facility will be furnished with a sufficient number of flashing lights inside the facility to warn any person that a radiographic exposure is about to take place. The flashing lights will be illuminated at least ten seconds before the radioactive exposure device can be activated. Flashing lights on the same time delay schedule will also be activated outside each entrance to the facility and in the control room.

h. Audible alarms will be provided outside the facility and operate for at least ten seconds before the radiographic exposure device can be activated.

i. All entrances to the radiographic facility will be provided with interlocks which will immediately terminate the exposure in the event that the door or gate is opened.

j. All radiographic facilities will be provided with emergency cords or switches which can stop the emission of radiation from its source by personnel who may be inadvertently in this room. These devices will be painted a conspicuous color. Arrows and appropriate signs will be posted in a sufficient number of places inside the room to direct personnel to the switch or cord in the event of an emergency.

5-3.1.2.4 Industrial Hygiene Procedures.

a. All personnel working in or frequenting a radiographic facility will wear film badges issued by the medical or industrial hygiene department. Visitors (including maintenance personnel, etc.) will wear dosimeters issued by the supervisory radiographer.

b. All personnel working in or frequenting a radiographic facility will receive a medical examination at intervals determined by the specific facility and in agreement with State regulations. A qualified medical authority will supervise the examination to make sure that no one has sustained radiation injuries.

c. A permanent file will be maintained for each employee involved in radiographic operations. It will include his name, identification, film badge readings, medical examination results, details of participation in operations involving radioactivity, and a record of any unusual exposures.

d. Permanent records will be kept of the periodic room surveys and the air sampler readings.

5-3.2 LIQUID PROPELLANTS.

5-3.2.1 General. Control of the quality of liquid propellants is a primary step toward safe operations. A propellant must, of course, be sufficiently pure that its performance is not degraded. But in addition, it is necessary to exclude or limit specific contaminants that might form hazardous accumulations, corrode the system, or catalyze the decomposition of the propellant. The content of solid particles, which might clog orifices or filters and damage valve seats, must also be limited.

For these reasons, users of liquid propellants must adopt purity specifications and back them up with sampling and analysis procedures. Inasmuch as these specifications and procedures may vary among different users, no attempt will be made to enumerate them; they are given in detail in, for example, military and NASA specifications and technical manuals. However, in order to gain some insight to the rest of this section, one should realize that liquid propellant specifications generally require that the propellant assay 98% or better; that specific impurities be limited to parts per million or even a fraction of a part per million (e.g., acetylene in oxygen); and that particulate matter not exceed a few milligrams per liter.

Assurance that liquid propellants will meet acceptable standards of purity requires a well-planned program incorporating the following elements: specification, procurement, handling, sampling, and analysis.

5-3.2.2 Specification. The Specification that is adopted should be responsive to real needs. When a maximum level is set for some contaminant, it should be done in consideration of the deleterious effects of that contaminant, or because the specified level is indicative of improper care in manufacture and handling. If unreasonably low levels are called for, the only results will be excessive cost for the propellant and difficulty in analysis.

5-3.2.3 Procurement. The supplier should be required to furnish a signed report of analysis on each lot of propellant to certify that it meets specification limits. An additional analysis upon receipt is not necessary unless there is some reason, such as a broken seal, to believe that contamination may have occurred in transit, or if the supplier's qualifications are questionable on the basis of prior local experience.

The supplier's analysis should be made on a sample taken from the transport container. This is to ensure that clean propellant is not transported in a dirty container.

5-3.2.4 Handling. Volume III of this manual describes in detail the correct methods of handling liquid propellants, and discusses material compatibility and cleanliness requirements.

Keep in mind that transfer lines, once connected, become part of the system and must be as clean and well-purged as the rest of the system. Transfer connections have a tendency to loosen because of repeated use. This should be prevented by good maintenance. The use of incompatible sealants must be prohibited.

Be sure that pressurizing and purge gases are sufficiently pure. (See Sect. 5-5)

5-3.2.5 Sampling. As a general rule, propellant should be sampled for analysis after each transfer, and periodically if it remains in one container for an extended length of time. The appropriate interval for periodic sampling will vary with the chemical reactivity of a given propellant, with its tendency to pick up contamination, and with the severity of the storage conditions (e.g., high and/or rapidly changing temperature, high humidity, atmospheric contaminant level, etc.).

5-3.2.5.1 Samplers. Devices used to obtain samples should be under the control of the analytical laboratory. After each use the sampler must be completely cleaned, dried, tested for leaks, and sealed in a clean plastic bag. It should be tagged with a signed certificate of cleanliness. All of these precautions are essential to prevent spurious contamination from showing up in a subsequent analysis.

5-3.2.5.2 Sampling Precautions. The person who obtains a sample must be thoroughly familiar with his equipment and with the properties and hazards of the propellant.

Adequate protective measures such as ventilation, breathing apparatus, and protective clothing must be used, as appropriate.

The danger of excessive pressures resulting from temperature rise after the propellant is collected in a sampler must be appreciated, and forestalled by leaving adequate ullage.

5-3.2.5.3 Sampling Procedures. The individual properties and conditions of storage of each propellant will dictate the detailed sampling procedure. For instance: the method used for a cryogenic liquid will necessarily differ from that used for a hydrocarbon fuel. Some features are common to all sampling procedures.

5-3.2.5.3.1 Sampling Point. Generally, the sample should be taken from a low point—in a pre-packaged system, from the very lowest point. If the propellant contains too much particulate matter, it is more likely to be found in such a sample.

5-3.2.5.3.2 Purging. The sampler and its connections must be thoroughly purged before the sample is trapped in it.

5-3.2.5.3.3 Identification. The sample must be completely identified and tagged with the name of the propellant, source, lot number, and any other pertinent information.

5-3.2.6 Analysis. This function should be provided by a qualified laboratory. Accepted procedures for analysis of liquid propellants can be found in the Handbook of the ICRPG Analytical Chemistry Working Group.

The analyst should maintain a complete and signed record of his work, including all calculations. This should be done, in ink, in a bound laboratory notebook.

5-3.3 GASES.

5-3.3.1 General. Both inert and reactive gases are used in rocket operations. The inert gases commonly required are helium and nitrogen. The reactive gases of most concern are oxygen, fluorine, and hydrogen. Both kinds of bases are subject to two kinds of problems: physical and chemical.

5-3.3.2 Physical Problems. Any gas at high pressure, regardless of its chemical nature, can be destructive because it contains potential energy. The rupture of a pressurized vessel can propel lethal fragments and initiate a blast wave. A broken flexible hose, if not restrained, will lash about violently until the supply of escaping gas is cut off. Improperly secured gas cylinders can become flying missiles if their contents are discharged in an uncontrolled manner.

5-3.3.2.1 Explosive Effects. Rupture of a pressurized vessel will release the potential energy of the stored gas with effects similar to those produced by a high explosive. This type of catastrophic failure is very rarely experienced with the usual coded vessels. However, the possibility of such a failure may be a source of concern when dealing with rocket propellant tankage. These tanks may be designed to lower safety factors than coded vessels and may have unusual and untried design features to meet specific mission requirements. The magnitude of a catastrophic tank failure can be conveniently expressed in terms of an equivalent amount of TNT by estimating the energy of adiabatic expansion. The standard ASESB Quantity-Distance Tables can then be used to determine the proper separation distance from a potentially-hazardous pressure vessel. For the case in which the rupture occurs at an ambient pressure of 14.7 psia, the following formula may be used (R. A. Boudreaux, 9th ASESB Explosives Safety Seminar, 1967, p. 183):

$$W_{TNT} = \left[(1.49 \times 10^{-3} V)/(\gamma - 1)\right]\left[(P/14.7) - (P/14.7)^{1/\gamma}\right] \quad \text{Eq. 5-1}$$

where:

W_{TNT} is the equivalent weight of TNT, pounds

γ is the specific heat ratio of stored gas

V is the storage volume, cubic feet

P is the storage pressure, psia.

5-3.3.2.2 Propulsive Effects. A type of accident that is all too common occurs when a connection is broken off of an unrestrained pressure vessel, and it behaves like a runaway rocket. People often do not appreciate the size of the unbalanced force tending to propel the vessel. For the case of gas escaping through a one-inch-diameter hole, a good rule of thumb is as follows: The force (pounds) is equal to three-quarters of the gas pressure, psig. Of course, as the gas discharges the pressure falls, so the force is greatest at the start. The force scales with the area of the hole; that is, it would be four times as great for a 1/2-inch hole as for the 1/4-inch hole given as an example for the rule of thumb.

5-3.3.2.3 Lashing Effects. It is often necessary to use high-pressure flexible hoses, and these may be broken while delivering gas. The violent lashing is extremely destructive; it might even damage a valve so that the flow could not be stopped. Therefore, flexible lines must be positively restrained. A very convenient method, and one of the few that are really secure, is to encase the hose in a Chinese-finger assembly (Cable Grip) made of stainless-steel cable. The ends of this assembly are attached to suitable anchor points. A ruptured hose restrained in this fashion will discharge without any whipping action whatever.

5-3.3.3 Chemical Problems. First, there is the matter of purity. Even the inert pressurizing of purged gases must be pure, because although the gases themselves will not react with the impurity, they will transport it to a region where it may react. In the case of cryogenic systems, purity has a further aspect: the gases used in the system must not contain foreign gases, even inert ones, that would freeze and thereby introduce harmful solid material.

The second kind of problem is one of the reactivity such as that of oxygen and fluorine and the flammability of hydrogen. The implications with respect to containment, ventilation, and system cleanliness and elimination of solid particles, are dealt with elsewhere in this manual. Brief mention will be made in this section of a special problem: hydrogen embrittlement of metals, Section 5-5.3.2.

5-3.3.3.1 Gas Impurity.

5-3.3.3.1.1 Contaminants. By reason of the methods of manufacture and handling, the following contaminants are apt to be present: water vapor, carbon dioxide, oxygen, nitrogen, and hydrocarbons.

5-3.3.3.1.2 Allowable Levels of Contaminants. Military and/or NASA specifications have been set up to control the purity of gases used in rocket operations. Some are listed below:

a. Oxygen
   - (1) Propellant: MIL-P-25508D, 16 Mar 1962
   - (2) Breathing: MIL-O-27210C (1) 29 Feb 1968
   - (3) Space Vehicle Grade: MSFC-SPEC-399A

b. Hydrogen
   - (1) Propellant: MIL-P-27201A, 1 Sep 1964
   - (2) Space Vehicle Grade: MSFC-SPEC-356A

c. Nitrogen
   - (1) Pressurizing: MIL-P-27401B, 19 Sep 1962
   - (2) Space Vehicle Grade: MSFC-SPEC-234A

d. Helium
   - (1) Pressurizing: MIL-P-27407 (1), 8 Jan 1965
   - (2) Space Vehicle Grade: MSFC-SPEC-364B

e. Fluorine MIL-P-27405 (1), 8 Nov 1968.

Fluorine's great reactivity insures that it will contain only contaminants toward which it is inert. However, one of these—hydrogen fluoride—can be very troublesome. It can be removed by passing the gas through a bed of sodium fluoride.

Helium and nitrogen used for pressurizing and purging liquid fluorine systems should exceed the specifications listed above. This can be achieved by passing the gas through a cartridge containing Linde Grade 13X molecular sieve, which will remove both moisture and hydrocarbons (H. W. Schmidt, NASA SP-3037, 1967, p. 206, reference 4).

5-3.3.3.1.3 Analysis.

5-3.3.3.1.3.1 Sampling Precautions. Gases should be sampled into stainless-steel containers. The sample-bottle connections must be free of leaks; air can migrate inward through a leaky connection in detectable quantities, even against a pressure as high as 50 psi. Teflon tape may be used to help seal connections.

It is not advisable to sample through ordinary pressure regulators, because they, too, permit inward migration of air and moisture. A good scheme is to use a sampling assembly consisting, in order, of a valve, a flow-limiting orifice, a pressure-relief valve capable of passing the maximum flow through the orifice, the sample bottle, and another valve. In use, the device is first thoroughly purged through the two valves, and a sample is then trapped for analysis.

5-3.3.3.1.3.2 Analytical Methods. A great many methods are available for the analysis of the contaminants in gases. Accepted procedures can be found in the Handbook of the ICRPG Analytical Chemistry Working Group.

5-3.3.3.2 Hydrogen Embrittlement. There is evidence that hydrogen at high pressure causes some metals to become brittle, even at ambient temperatures. Martensitic stainless steels such as type 403 definitely should not be used to contain pressurized hydrogen. Other metals may be subject to embrittlement as well, but positive statements as to their safe conditions of use cannot be made at present because research results are not yet conclusive. Meanwhile, the use of stainless steel or perhaps aluminum liners is one safe solution for the construction of large, high-pressure vessels for hydrogen.

5-4 METEOROLOGICAL CONSIDERATIONS (References 11 to 24)

5-4.1 GENERAL. The ever-increasing use of toxic propellants to improve the performance of solid and liquid rocket propulsion systems has made meteorological considerations to an integral part of test and launch operations. It is imperative to be able to predict the general downwind area that could be affected by the trajectory of a toxic exhaust cloud. It is also imperative to be able to estimate the possible exposure that could be received by personnel located within this area and minimize the toxicological hazard.

Making these predictions is not an exact science and a great deal of work is still necessary before a high degree of accuracy will be attained. However, prediction of the worst possible case under given meteorological conditions can be performed with a fair degree of confidence and establishment of a meteorological forecast program is mandatory.

It is highly desirable to establish the climatology at the operational site. This information will provide historical data on conditions such as prevailing winds, inversion layers, and storm seasons. This data is invaluable in helping to determine favorable operational periods and periods when operations are generally impractical. Obtaining the climatology is a tedious and time consuming process at best and requires several years of data to acquire an accurate pattern. However, even a year's data will prove helpful in determining favorable operational periods.

The main objective for successful operations is to conduct them in a weather pattern that will insure that the exhaust cloud follows the predicted trajectory with no toxicological hazard to site personnel or to the general public. The meteorological requirements necessary to provide success will have been determined by the size of the propulsion system, the controllable access boundary area downwind, the population density, topography, etc.

5-4.2 SPECIFIC METEOROLOGICAL REQUIREMENTS. The precautions that must be observed in order to provide satisfactory firing conditions vary with the quantity of propellant used in the propulsion system being utilized, the controllable access boundary area downwind, the population density, topography, etc. The three most important meteorological variables to be considered are temperature difference, wind direction, and wind velocity.

5-4.2.1 Temperature Difference. The temperature difference (ΔT) between two different levels defines the atmospheric conditions within the bounded region. They can be unstable or lapse (defined by a negative value of ΔT), neutral, and stable or inversion (defined by a positive value of ΔT). In practically all situations, unstable (lapse) atmospheric conditions are a requirement for safe operations.

5-4.2.2 Wind Velocity. To provide a high degree of confidence that an exhaust cloud will closely follow the predicted trajectory, a wind velocity of some magnitude is necessary. Generally, a constant five mph is considered an absolute minimum. Gusts of this or higher magnitude are not considered satisfactory if the velocity consistently dips below the five mph level.

5-4.2.3 Wind Direction. A satisfactory wind direction is determined by the downwind area the exhaust cloud will traverse. Controllable areas, population, and topography must be considered. Wind velocity will also affect the variance in direction during the time of cloud passage. Generally, the higher the velocity the less the variability in direction.

5-4.3 FACILITY METEOROLOGICAL SITUATION. It is necessary to forecast the meteorological situation that will be prevalent during firing operations. The general weather pattern for the area of the facility can be obtained from the nearest office of the U.S. Environmental Science Services Administration (ESSA). The project meteorologist can use the information available at the station if it is nearby. The meteorologist on duty can help provide information if the station is an inconvenient distance away.

5-4.5 METEOROLOGICAL EVALUATION. Evaluation of the meteorological control program established must be accomplished by data reduction and analysis. Plots of the radiosonde and radar data will establish the conditions in the upper air and how they affected the exhaust cloud trajectory. Various computer routines have been developed to handle this data as well as that available from the surface instrumentation. The effect of the surface conditions on the exhaust cloud can also be established.

Analysis of these data may reveal that additional instrumentation is required or that the location of some installations needs to be changed. Certain trends may become apparent that will prove to be good predictors of local variations and changes. Prediction equations may have to be modified to include different parameters or eliminate those that prove of no consequence. Continual evaluation of the meteorological control program will help to improve scheduling and decrease cost.

5-5 LEAK DETECTION OR ENVIRONMENTAL MONITORING

5-5.1 GENERAL. Leak detection is a primary function of hazard-monitoring systems. Liquid rocket propellants are, by definition, either flammable or strongly oxidizing, and many are corrosive and toxic as well. Therefore, they must be contained, and leaks must be detected promptly so that timely action can be taken.

This function must be performed by some kind of self-contained, direct-reading instrument. It may or may not be automatic, depending on the response time required and on the feasibility of having a human observer present. In a storage area, for example, leaks might be expected to develop slowly, and visual inspection plus a sense of smell might be sufficient. This does not imply fixed, or permanent detection systems should never be used in storage areas—the particular situation governs the decision. If desired, the actual concentration of propellant vapor in the air could be measured with one of the many hand-operated detectors that are available (reference 5). In test or launch areas, however, more elaborate devices are required. Here propellants are pressurized and flowing rapidly; therefore, leaks can develop very quickly. Observers must keep to a safe distance. Therefore, the leak detectors must operate automatically, respond quickly, and read remotely. The rest of this section will deal with instruments of this kind. Some examples of specific instruments are given in Appendix D, Volume III of this work.

5-5.2 PRINCIPLES OF DETECTION. Automatic leak detectors operate by measuring a physical property that is related to the presence of leaking propellant. In some cases, the property measured is inherent in the substance; in others, it must first be developed by some kind of treatment, such as a chemical reaction of the propellant vapor with a reagent contained in the instrument. Both the kind of physical measurement made and the sensitizing treatment, if any, determine how specific the detector will be for leaks of a particular propellant.

The most widely-used principles of detection are as follows:

Ionization
Electroconductivity
Radiochemical Exchange
Paramagnetic Behavior
Thermal Combustion
Infrared Light Absorption
Condensation Nuclei Counting
Chemiluminescence
Electrochemical Reaction.

Although some progress has been made in detectors in recent years, none of them are entirely satisfactory. The need is for instruments which will differentiate quantitatively and rapidly between specific propellants in the presence of each other. The placement of detectors/samplers must be carefully planned in order to assure that leaks will be detected at the onset. It is extremely important that instruments be kept properly calibrated, that the sensitivity range be realistic for the particular operation involved and that records be kept of contamination levels experienced in the areas monitored.

5-5.2.1 Ionization. This technique is based upon the use of an ionization chamber to detect an aerosol which can be formed from the contaminant in different ways. Continuous ionization of the sample is provided by a mild alpha source. Pure air in the chamber shows a constant flow of ion current but very small concentrations of particulate matter produce a drop in current flow. Formation of the aerosol is accomplished either by chemical reaction or by direct pyrolysis of the sample. The major drawback of this instrument is its lack of specificity.

5-5.2.2 Electroconductivity. The operation of this detector is based upon the change of conductivity of pure deionized water resulting from the solution of the gas sample. The increase of conductivity in the water is proportional to the ionizable toxic gas in the sample. Many gases which do not ionize are broken down in a pyrolyzing furnace so that they will ionize readily in water. The level of toxic gas concentration can be continuously indicated by a recorder. The system is applicable to all gases that can be ionized. It is not specific since it indicates all ionizable gases.

5-5.2.3 Radiochemical Exchange.

5-5.2.3.1 Clathrates. This method involves the use of radioactive krypton-85 trapped in a three dimensional organic crystalline cage called a "clathrate". The trapping cage molecule is hydroquinone. Any gas that will oxidize with the hydroquinone will react with the clathrate to release krypton-85. The radioisotope can then be measured by a conventional radiation detection device such as a Geiger counter. The quantity of radioisotope released is proportional to the amount of the reacting species. One of the main problems with the clathrate system has been its humidity dependence and slow response time, but it has been reported that these problems have been corrected.

5-5.2.3.2 Kryptonates. Kryptonates are solid materials containing the radioisotope krypton-85. The gaseous isotope is incorporated into a solid material by means of ion bombardment or by exposures of the material to krypton gas at high temperature and high pressure. The kryptonated source will lose its activity when reaction occurs between itself and a gaseous constituent. The resulting loss of radioactivity is proportional to the concentration of the reacting gas. The possibilities of different types of kryptonates that can be applied as detection sensors for various gaseous species are numerous. Thus the kryptonates do not only have the advantage of sensitivity but there is also the freedom to choose efficacious reactions resulting in excellent selectivity and discrimination.

5-5.2.4 Paramagnetic Behavior. Oxygen is unique among gases in being strongly paramagnetic—attracted into a magnetic field. Other gases are with a few exceptions, slightly diamagnetic—repelled out of a magnetic field. Thus by measuring the magnetic susceptibility of a gas, the oxygen content can be determined. The instruments are simple and have proved to be very accurate.

5-5.2.5 Thermal Conductivity. There are two classes of detectors which depend on thermal conductivity changes. One method is based on the difference of thermal conductivity of the gas to be detected from that of the air. The other more frequently used method is only applicable to fuels. It detects the temperature increase due to the heat of combustion. A change in the temperature of a wire can be indicated by measuring the resulting change in its electrical resistance. A gas sample is pumped through the detector filament chamber. Any combustible gas or vapor in the sample burns on the surface of the hot detector filament—thus the heat of combustion increases the temperature of the detector filament compared with the compensator filament which is not exposed to the gas sample. The increased temperature proportionately increases electrical resistance and unbalances the Wheatstone Bridge circuit. This electrical unbalance actuates indicating meters or recording potentiometers. The change in resistance is proportional to the gas concentration up to and including the lower explosive limit.

5-5.2.6 Infrared Light Absorption. All liquid propellants except the elements such as oxygen, hydrogen, and fluorine absorb light at characteristic wavelengths in the infrared part of the spectrum. Two similar Nichrome filaments are used as sources of infrared radiation. Beams from these filaments travel through parallel stainless steel cells. One beam traverses the sample cell and the other the comparison cell. As the gas in the detector absorbs radiation its temperature and pressure increase. An expansion of the detector gas causes a condenser microphone membrane to move. This movement when electrically amplified produces an output signal. The electrical signal is proportionate to the difference between the two radiation beams and to the vapor concentration.

5-5.2.7 Condensation Nuclei Counter. The Condensation Nuclei Counter (CNC) provides for the continuous measurement of trace airborne contaminants.

The CNC measures particles of airborne contaminants as small as a nanometer in diameter and detects mass concentrations of 10^{-16}g/cc.

The CNC utilizes the properties of submicroscopic particles to act as the nucleus for the formation of visible water droplets in a cloud chamber.

The CNC, with minor adaptations, can be used to detect trace concentration gases. This capability stems from the fact that many gases can be converted into submicroscopic particles. The gas to be detected is converted to a low vapor pressure substance producing either a liquid or solid particle.

5-5.2.8 Chemiluminescence. The basic principle of this device follows. The gas to be monitored is aspirated past a surface coated with a chemiluminescent material (rhodamine B adsorbed on silica gel). If fluorine is present in the gas, the surface of the silica gel glows due to an oxidation reaction. This glow is sensed by a photomultiplier tube, and the magnitude of the signal is directly proportional to the fluorine concentration if the flowrate is constant. However, the signal increases with increasing flowrate through the cell. It is, therefore, important to maintain a constant flowrate through the detector. The sensitivity of the system can be increased by higher flowrates. The above principle has been demonstrated to be reliable and specific for fluorine.

5-5.2.9 Electrochemical. Propellant vapors that ionize can be scrubbed out of the sample airstream, by pure water and be detected by the increased electrical conductivity of the water. In another type of device, the vapor is used as one of the reagents in an electrochemical cell. The ensuing reaction generates an electric current that depends upon the concentration of propellant.

5-5.3 CALIBRATION. All types of leak detectors must be checked regularly by exposing them to known concentrations of propellant vapor. This is not always a simple matter. Detectors for some of the more toxic propellants may have full-scale readings in the parts-per-million range, and the preparation and successful delivery to the instrument of such a dilute mixture call for great care. Reference 6 gives an excellent discussion of this subject.

5-5.4 SELECTION FACTORS FOR LEAK DETECTORS

5-5.4.1 Suitability. The obvious prime factor to consider in choosing a detector is its ability to respond to the propellant. Table 5-1 lists the liquid propellants and indicates types of detectors that are applicable to each. The material in this table is based on a survey of manufacturers' statements, and may be incomplete.

5-5.4.2 Specificity. Table 5-1 shows that some of the operating principles have been utilized in detectors for several different propellants, and this suggests the possibility of interference if two or more of these propellants should be present in an area. Furthermore, the more sensitive types of detectors may also respond to background contaminants that are often present in air.

Table 5-1

Detection Methods*

Gas To Be Detected	Detection Method: Ionization	Electroconductivity	Radiochemical Exchange	Paramagnetic Behavior	Thermal Combustion	Infrared Light Absorption	Condensation Nuclei Counting	Chemiluminescence	Electrochemical Reaction
Alcohols	•				•	•			•
Ammonia	•	•			•	•			
Boranes	•				•	•			•
Fluorine and FLOX	•	•	•					•	•
Halogen Fluorides	•	•	•					•	•
Hydrazine and MMH	•	•	•		•	•	•		
UDMH and MAF	•	•					•	•	•
Hydrocarbon Fuels	•				•	•	•		
Hydrogen			•		•	•	•		
Methane					•	•			
Nitric Acids	•	•				•	•		•
N_2O_4 and MON	•	•	•			•	•		•
Oxygen				•					•
Oxygen Difluoride	•								
Pressurizing Gases**				•					

*Compiled from literature supplied by responding manufacturers of automatic remote-indicating instruments which are commercially available.

**Only to determine if the atmosphere contains sufficient oxygen for breathing purposes.

Some of these are sulfur and nitrogen oxides, carbon monoxide, hydrocarbons, solvents, inert pressurizing gases, and particulate matter. In choosing detectors for a given application, interferences should be carefully considered and the suppliers of candidate instruments consulted. See also reference 6 and data in Appendix D, Vol. III of this work.

5-5.4.3 Response Time. It is not possible to give definite response times for each type of detector. There are, however, two general considerations:

a. Devices that measure an inherent property of the contaminant are faster than those in which a measurable property must first be developed. For instance: at a given level of contamination, infrared-absorption instruments are faster than those in which visible-light absorption must be produced by reaction of the contaminant with a reagent.

b. There will usually be a trade-off between sensitivity and response time. The more insensitive the detector, the larger the sample volume must be, and the longer it will take to collect and purge out the sample.

These two considerations alone account for a range of response times (considering all the types of instruments) from one second to more than five minutes.

Another, more specific determinant must be kept in mind. If several potential leak-sites are sequentially sampled into a common detector, or if the sample line to a remote station is overlong, the response may be intolerably slow. There have been cases of this kind in which enough flammable vapor leaked out to cause an explosion, and yet the leak was never detected. Whenever such a thing could happen, it is necessary to invest in multiple detector stations.

5-5.4.4 Range. The range of concentrations over which a detector is to function should be specified realistically. Often, there is a temptation to set the range very low on the theory that a sensitive detector will give an early warning. But such a detector may turn out to be useless because it is constantly responding to interfering substances or to a low background of propellant vapor that is unavoidably present.

Where people are constantly exposed to potential leaks of toxic propellants, the range of the detector must cover the threshold limit value, a ceiling if one is specified, and one or more of the time dependent emergency exposure limits. Where leaks can only occur during remote operations, less sensitivity may be desirable, with the range being set more by considerations of vapor pressure than toxicity.

In the case of flammable but relatively non-toxic vapors, combustible-gas detectors are most often used. Their range is chosen to include some percentage of the lower explosive limit (20% of the LEL, volume percent) of the vapor in air.

5-5.4.5 Environmental Factors Affecting Instrument Response. Many leak detectors are sensitive to changes in sample temperature and/or humidity. Large and sudden changes in these factors are the norm around rocket test or launch areas. Various means can be used to compensate for such effects so that the instrument will respond correctly, and the user should make sure that suitable compensation has been included.

A special environmental effect occurs with some combustible-gas detectors designed for hydrogen. Instead of continuing at full-scale as hydrogen concentration rises above the LEL and into the flammable region, their reading first rises to and then falls below full-scale. Not knowing this characteristic of the instrument would cause an observer to think that a dangerous condition was improving, when it was in fact becoming worse.

5-6 FIRE DETECTION (References 7 and 8)

5-6.1 GENERAL REQUIREMENTS.

Fire detectors should be used wherever prompt warning of a fire would permit action to be taken that could minimize injuries, facility damage, or schedule delays.

The choice of a type of warning system (and of a fire strategy in response to the warning) will be dictated by the nature of the hazard. The key factors are the likely intensity, duration, and extent of the fire, and the type of combustible involved.

5-6.2 DETECTOR TYPES

5-6.2.1 Heat Sensitive. These devices respond to temperature rise. They are available in a wide variety of forms including those which rely upon pneumatic tubes or bulbs, thermostats, and wires which short when temperature sensitive insulation melts. Some are made to respond only to the high rate of rise accompanying a fire, so that they can be used without giving false alarms in situations where a slower temperature rise is normal.

5-6.2.2 Smoke Sensitive. These photoelectrically detect the attenuation of a light beam by smoke.

5-6.2.3 Flame Sensitive. These photoelectrically observe light emitted by flames and may operate in the ultraviolet, visible, or infrared parts of the spectrum. The latter two types generally must have an electrical circuit that is insensitive to DC and slow AC signals, so that the flickering light of a flame can be distinguished from harmless sources. Even so, flicker-sensitive systems may sometimes be spoofed by such sources as light shining through the blades of a fan or reflecting from reciprocating machinery.

The ultraviolet systems are not troubled by such considerations. The detectors are made insensitive to normally occurring sources of light and respond only to the ultraviolet wavelengths emitted by all flames. In the case of hydrogen flames, no other type of flame detector will serve; burning hydrogen emits little or no visible light, and its low level infrared emission is strongly absorbed by water vapor in the air.

5-6.3 APPLICABILITY OF VARIOUS DETECTOR TYPES

5-6.3.1 Heat Sensitive. Because they are basically mechanical in operation, heat detectors respond less quickly than the photoelectric types. Also, they must be directly exposed to the heat of a fire in order to respond. For these reasons, heat detectors are best used in those enclosed or semi-enclosed spaces where fires are not expected to develop with catastrophic speed. In such applications, their virtues of time-proven simplicity and low cost outweigh their limitations.

5-6.3.2 Smoke Sensitive. Once smoke enters the light beam, these devices respond very quickly. The problem of ensuring that smoke promptly enters the beam generally restricts the use of smoke detectors to confined spaces. They may also be useful in ventilation systems, particularly where an outbreak of fire is likely to be preceded by a smoldering phase. Such detectors are obviously useless for combustibles like hydrogen or alcohol, which burn without emitting smoke.

5-6.3.3 Flame Sensitive. When the application calls for a fire detector that responds quickly and gives broad area coverage, photoelectric flame detectors are the best choice. The ultraviolet type is the most specific for flame radiation and is, therefore, the least likely to give false alarms.

5-6.4 VISUAL DETECTION.

In many operations the danger of fire only exists for a relatively short time, and it may be possible to assign an observer to watch for it. Television viewing of inaccessible areas is useful and special image tubes are available that show flame radiation brightly, even in strong sunlight.

5-7 ACOUSTIC DETECTORS

5-7.1 GENERAL REQUIREMENTS. The acoustic hazards to man due to exposure to high intensity noise will be discussed in Chapter 7. Proper evaluation of this type of hazard requires that the hazardous environment be adequately defined. This will frequently require some means of monitoring high intensity noise levels. This may be accomplished with permanently installed or portable acoustic instrumentation. The type of data to be obtained and the general characteristics of the instrumentation itself are considered in this section.

5-7.2 DATA REQUIREMENTS. An acoustic environment can ordinarily be specified in terms of its intensity as a function of frequency and the time variation of this intensity spectrum. The parameters of intensity, frequency spectrum, and time variation, must be monitored.

5-7.2.1 Intensity. Due to the wide range in acoustic pressures that are sensed by the human ear, the intensity of an acoustic field is specified by a logarithmic scale in terms of the decibel (dB). For example, the term SOUND PRESSURE LEVEL (SPL) is used to specify a sound pressure (P) logarithmically as

$$SPL + 20 \log_{10} (P/P_{ref})$$

The reference pressure (P_{ref}) is normally taken as 0.0002 dynes/cm^2; close to the human threshold of hearing in the mid-frequency range. Sound pressure levels hazardous to man will generally fall in the range between 80 dB (the minimum sound level for hearing damage risk) and 150 dB. Although higher sound pressure levels, up to 180–190 dB, may be measured very close to rocket engines, man should never be exposed to noise fields above 150 dB. Sound fields in the range of 40–80 dB, while not hazardous, may be annoying for some residential areas and work locations.

5-7.2.2 Frequency Spectrum. The frequency content of most hazardous noise sources can be conveniently defined by the intensity within each of a set of continuous frequency intervals. Sufficient frequency discrimination is ordinarily provided on one third octave band filters. These filters divide a two to one frequency interval into three parts, each having a bandwidth equal to about 26% of its center frequency. In the frequency range of 20–20,000 Hz, the maximum range of audibility for the human, then, are 30 one-third octave band intervals. Engine noise from large rocket boosters will require a frequency analysis from about 2 Hz–2000 Hz to define its principal spectral content. However, an analysis up to 10,000–20,000 Hz may be desired to completely evaluate the acoustic hazards for man.

5-7.2.3 Time Variation. For relatively constant acoustic noise fields, such as observed near a static firing stand for rockets, time variation of the average acoustic level may not be significant. On the other hand, during launch of a rocket booster, a rapidly changing sound level may be observed, particularly at the higher and more hazardous sound levels close to the launch stand. In such a case, some means of portraying the time variation in the overall (unfiltered) sound level or in each filtered band may be required. For example, a useful definition of the hazard of a transient acoustic environment would consist of the envelope of maximum band levels, regardless of the time of occurrence of the maximum in each band. Such a composite spectrum would require that time variations in the spectral content be measurable. These time variations are normally portrayed by playing back a recorded sample of the sound through ink-writing or oscillographic recorders.

5-7.3 INSTRUMENTATION REQUIREMENTS. A detailed consideration of acoustic instrumentation is beyond the scope of this manual. The reader is referred to references 9 and 10 for specifics. It will be sufficient here to list a few of the essential features for acoustic instrumentation systems. In general, two types of monitoring systems may be employed; semi-permanent systems installed to observe sound pressure levels at fixed locations; and portable or hand-held sound level meters. The former type of system is required in areas close to rocket test stands where sound levels are of the order of 120–130 dB or more. At these locations, potential hazards from an accidental explosion will generally preclude the use of portable hand-held instruments. Such "installed" systems generally consist of the following major elements:

a. Microphones and holders which are rugged and reliable for field operation, have uniform or smooth frequency response, are relatively insensitive to mechanical vibration and which have high acoustic sensitivity

b. Signal conditioning equipment with electronic amplifiers capable of accepting low signals over long lines and with adjustable and preset gain steps for calibration purposes

c. Signal recording equipment with multichannel magnetic tape recorders

d. Spectrum analysis equipment

e. Time history graphic recorders.

These special acoustic measurement systems are normally assembled to custom requirements from commercially available components.

Portable hand-held sound level meters are widely used to spot-check potentially hazardous acoustic environments. Personnel exposed to potentially damaging sound levels must be protected with ear protectors or ear muffs. Safety or medical personnel are often charged with the responsibility to obtain necessary acoustic data to evaluate the need for such personnel protection. These portable sound level meters must meet standard performance criteria for accuracy, intensity range, speed of response, frequency bandwidth, etc., as established by the American Standards Association. A number of commercial units are available, some with built-in frequency analyzers. Very few of these devices are capable of making accurate measurements below 20–40 Hz. They are subject to error, therefore, when being used to measure wide-band noise levels of large rockets. However, the important frequency range for acoustic hazards to humans will normally be adequately covered by such portable units.

5-8 VIBRATION AND ACCELERATION (References 25 to 29)

5-8.1 GENERAL MEASUREMENTS. Seismic ground-motion measurements have been obtained from a large number of launches, from intentional destruct tests, and from propellant-explosion tests covering a wide range of propellant weights. The results show that at distances greater than about 1000 feet from the source, the ground-propagated seismic energy does not cause hazardous vibrations. It remains, however, to consider the effects of the air-propagated blast and sonic waves, as well as the near-field vibrations.

5-8.2 SONICALLY-COUPLED GROUND MOTION. Measurements of ground motion from launches and propellant explosions have shown that the strongest component of motion coincides with the arrival of the overpressure wave. In other words, the air-transmitted wave induces ground motion. As shown in Chapter 2, the pressure waves required to induce damaging ground motion are themselves above the threshold for structural damage. Therefore, blast-induced seismic disturbances are less hazardous than the direct effects of the blast.

5-8.3 SONICALLY-INDUCED VIBRATION. Despite the foregoing statements, it is still necessary to consider vibration effects on structures. These effects can be induced by acoustic energy below the level of blast damage; they occur because air-transmitted impulses can couple efficiently to a structure if the input frequency matches a normal vibrational mode. This situation is in contrast to normal wind-loading, which is accounted for in structural designs on the assumption that wind loads are quasi-static.

It is recommended that structural-vibration measurements be made wherever the possibility of damage exists. Two stations should be operated in structures over 100 feet high, recording three components of particle velocity in three orthagonal planes. One station should be at the tip of such a structure and the other at the bottom. Induced vibration at levels less than 2 cm/sec can generally be neglected.

5-8.4 NEAR-FIELD VIBRATION. At distances less than 1000 feet from the source, the structures directly associated with test or launch will be subjected to both acoustically- and seismically-induced vibrations. The loads that must be sustained have been thoroughly investigated during actual firings and propellant explosions.

5-9 ACCIDENT EVALUATION

5-9.1 OVERPRESSURE AND THERMAL FLUX. Although many tests have been made to determine the blast and thermal effects of propellant explosions, it has not been economically feasible to test the extremely large quantities used in some systems. For these large facilities in particular, therefore, it is important to provide instrumentation to assess blast and thermal effects in case an accident should occur. The information gained could be extremely important, not only in evaluating off-site damage claims, but also in planning future operations.

5-9.1.2 Overpressure Instrumentation. The system consists of an array of pressure sensors, any requisite amplifiers or signal-conditioning equipment, and tape recorders (references 30 and 31).

5-9.1.2.1 Arrangement and Sensitivity of Sensors. Side-on pressure-time data must be obtained at several distances from the source in order to determine yield and impulse. Inasmuch as the blast wave from a propellant explosion may be highly asymmetric, sensors must be distributed in azimuth as well as distance; they may be placed along three radial legs 120 degrees apart, or spaced along a spiral expanding from the source. The outward spacing must be determined from the potential yield. The yield may of course vary from 0 to 100+ percent, in terms of pounds of TNT, so an intermediate yield must be chosen in order to fix the distance from the source of the closest sensors. A reasonable procedure is to assume a 10 percent yield, and to place the first ring of sensors at a distance, as determined from the charts in Chapter 2, that will experience a 100-psi overpressure from an explosion of this amount of TNT. The dynamic range of the nominal 100-psi sensors should be great enough to handle the overpressure from yields 10 times larger and smaller; this should pose no problem, because the overpressure at a given distance scales with only the 1/3 power of the yield in pounds. In addition to the closest ring, three more at successively greater distances are recommended. The sensors on the most remote ring may be nominally 1-psi rated. In addition, it may be desirable to have one or two sensors very close to the source; these may be rated at 5000 psi.

5-9.1.2.2 Characteristics of Sensors. The bandwidth of the overpressure system as a whole should be DC to 10 or 20 kc. Piezoelectric pickups that meet the requirements are available with short rise times and high natural frequencies, up to 20 kc or better.

The sensors and associated preamplifiers or charge amplifiers must be rugged and unaffected by changes in the ambient environment.

It is recommended that sensors be mounted to measure side-on overpressure. Therefore, the dimensions should be small (less than 1/2 inch in diameter) to minimize the transit time of the blast wave across the sensitive surface.

5-9.1.2.3 Recording Equipment. Two 14-channel tape recorders will provide enough capacity for both the overpressure and thermal flux data. They must be run at sufficient speed to provide the required time resolution.

5-9.1.2.4 Calibration. The sensors themselves should be checked in a facility, such as a shock tube, that can subject them to shock waves of known amplitude. Once their accuracy has been ascertained and the sensors have been installed in the field, an electrical signal can be used to check calibration at the time the system is turned on.

5-9.1.3 Thermal-Flux Instrumentation. The temperature of the fireball accompanying a propellant accident is a characteristic of the particular propellant combination. The thermal flux transferred to objects immersed in the fireball, however, depends on the scale of the accident. The heat is transferred both by radiation and convection inside the fireball; as a practical matter, it is not too important to separate the two effects. Therefore, in order to assess the thermal loads sustained by various objects, it is recommended that the combined effects be measured by calorimeter-type gauges. These are slabs of metal in which a thermocouple is embedded so that it reads the temperature just below the surface of the metal (reference 32). It may also be desirable to locate a radiant-energy gauge (reference 32) outside of the likely maximum boundaries of a fireball.

5-9.1.3.1 Location of Gauges.

a. Calorimeter gauges may be located on the test or launch structure. Two are generally sufficient—one at a high and the other at a low level. It may be desirable to make each redundant.

b. Radiant-energy gauges should be located outside the potential fireball. Fireball sizes can be estimated from the data in references 33 and 34. To allow for possible asymmetries, two gauges located 180° apart should be used.

5-9.1.3.2 Construction, Theory, and Calibration. Reference 32 contains a thorough discussion of the various types of thermal-flux gauges, their theory of operation, inherent errors, and calibration.

5-9.2 *FRAGMENT ANALYSIS.* Information about an explosion can be inferred from a careful examination of the resulting fragments. This information is of two kinds; the details of the explosion—its cause, point of origin, and propagation; and its magnitude.

It is often possible to deduce a great deal about the step-by-step events from an analysis of the fragments, but an estimate of the yield, or magnitude, of the explosion must rely on a correlation between fragment distance and yield.

5-9.2.1 Details of the Explosion. After an explosion, everything that was not vaporized still exists and some of it carries tell-tale information. The procedure for obtaining it will be summarized briefly. For a detailed discussion and examples of the method, see "The Study of Missiles Resulting from Accidental Explosions—A Manual for Investigators," AEC Safety and Fire Protection Bulletin 10 March 1966, by Crosby Field.

5-9.2.1.1 Fragment Identification. The identification of fragments from an explosion consists of matching insofar as possible, each fragment with its location on the vehicle prior to the explosion. It is necessary to have detailed information on the constructional details of the vehicle, such as skin material and thickness; location, size and material of protuberances, such as pipes, ducts, valves, domes, motors, etc. Matching a protuberance is not difficult because of the characteristic shape of each protuberance, its known dimensions and constituents. Skin fragments must be scrutinized for the presence of peculiar features such as chemical milling, attachments and rivets, as well as material and thickness. Finally, if the recovery of fragments is nearly complete, it may be possible to reconstruct a part of the vehicle, like a jigsaw puzzle, in order to identify the original location of each fragment within a group of fragments.

5-9.2.1.2 Fragment Trajectory. The exact location of every fragment that the investigator believes can be identified should be plotted. From the manner in which the fragments from the same piece of equipment are disposed—i.e., whether they be on a circle, form a V, etc.—it is possible to state whether the explosion occurred at the center, to one side, or outside of the equipment. However, care should be taken not to rely too heavily in the investigation upon sheet-metal fragments or others that are light and have a large surface area; these often follow an erratic course.

5-9.2.1.3 Examination of Fragments. Each important fragment (i.e., each one whose source can be identified) should be examined for evidence of its history. Some pieces may have been struck or pierced by another missile, or may show evidence of having struck steel or concrete members. Others may reveal evidence that they were in a fire or were subjected to a heavy electric discharge. Such knowledge can be crucial in reconstructing the event.

5-9.2.1.4 Reconstructing the Accident. With the foregoing evidence in hand, the investigator is in a position to form hypotheses about the cause of explosion and subsequent events. In order to arrive at the proper conclusion—or at least, the best conclusion—it is essential that all the fragment information be used. A cursory study of a few fragments will often suggest an explanation, but the evidence from others will refute it. The aim is to discover the one sequence of events that is consistent with all the results.

5-9.2.2 Magnitude of the Explosion. As indicated in Para. 5-10.2, the estimation of yield from a study of fragments is not an exact science. However, it is possible to obtain a rough idea, and combined with other evidence such as the maximum conceivable yield, it may be valuable. In order to make the estimate, it is only necessary to measure the maximum distance at which fragments are found, omitting light pieces with large surface area. Then, refer to Figure 5-1, where maximum fragment distance is plotted against weight of explosive. This figure is plotted logarithmically and the data form a broad band; thus, one cannot expect a precise estimate of explosive yield from fragment range.

5-10 ACCIDENTIAL TOXIC PROPELLANT SPILLS

5-10.1 GENERAL. In most instances, there are no fully satisfactory methods of arranging toxic sensors to sample an accidental toxic release or spill. This is because the vagaries of wind, weather, and terrain make it extremely difficult to predict where sensors should be positioned, particularly at considerable distances from the site, so as to intercept the toxic cloud.

5-10.2 EMERGENCY PROCEDURES. Under the recommendations of this chapter, facilities using toxic propellants are sited for the worst case after a detailed micrometeorological study of the area has been carried out. Even so, emergency procedures must be implemented to deal with accidental releases. It is recommended that periodic drills be held so that personnel will be familiar with the actions required. If an accidental spill or release occurs, the emergency plan must be put into effect immediately.

5-11 EVALUATION

It is essential to begin the evaluation of an accident or incident as soon as possible, otherwise, evidence may be removed or lost and memories obscured. An important feature of the evaluation is to compare the circumstances and effects of the accident or incident with data from previous operations or any other accident or incident that may have occurred, in order to identify trends or related causative factors which will enable corrective action to be taken. All data should be thoroughly documented and information disseminated to interested parties with existing security restraints.

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CHAPTER 6

TRANSPORTATION AND RELATED ACTIVITIES

6-1 PURPOSE

The purpose of this chapter is to cover the more general aspects of transportation regarding chemical rocket/propellant hazards; whereas solid propellant-related transportation, including a rather detailed coverage of all types of explosives and other dangerous articles appears in Volume II, Chapter 4 and a transportation section is included in each individual propellant chapter in Volume III.

6-2 GENERAL REMARKS

This chapter deals with Department of Transportation (DoT) hazardous materials regulations development, responsibilities, enforcement, areas undergoing change, and the location for obtaining specific information. Mention is made of the United Nations labeling system for hazardous materials. Because of the extensive use of contractors by Government organizations, this subject (particularly the military aspects of contractor-related transportation of ammunition, explosives and related dangerous material) is covered herein also. It is essential that all persons involved in transportation and related aspects of chemical rockets/propellants be well-versed in the hazards of all materials being handled and in the Federal, State and local laws and regulations pertaining thereto. The material included in this chapter is only a portion of the total picture—chosen to present highlights.

6-3 DEPARTMENT OF TRANSPORTATION REGULATIONS

6-3.1 THE DEPARTMENT OF TRANSPORTATION ACT (80 Stat. 931). This Act transferred to the Secretary of Transportation the regulatory authority in various sections of law relating to the shipment and transportation of hazardous materials by all civil modes of transportation.

6-3.2 SHIPMENT AND TRANSPORTATION OF HAZARDOUS MATERIALS. The secretary in turn delegated his functions relating to regulation of shipment and transportation of hazardous materials by air, water, highway and railroad and pipeline to the Federal Aviation Administrator, the Commandant, U. S. Coast Guard, the Federal Highway Administrator, and the Federal Railroad Administrator, respectively. (See section 6(c)(1) and 9(e) of the Department of Transportation Act and Part 1 of the Regulations of the Secretary.) (49 Code of Federal Regulations (CFR), Part 1)

6-3.3 HAZARDOUS MATERIALS REGULATIONS BOARD (HMRB). The HMRB was created by Departmental Order 1100.11 on July 27, 1967.

6-3.3.1 Purpose. To make it possible for shippers and carriers to be able to refer to a cohesive set of authoritative regulations upon which they may rely in preparing, shipping and transporting materials regardless of the mode of transportation. Shipments of hazardous materials may move through all or several of the modes of transportation over which the heads of the operating administrations of DoT have cognizance.

6-3.3.2 Composition. The Board is composed of the Director of the Office of Hazardous Materials (OHM) as Chairman and the Commandant, U. S. Coast Guard, Federal Aviation Administrator, Federal Highway Administrator, the Federal Railroad Administrator, or designees, as members. The General Counsel of the DoT is the legal advisor to the Board.

6-3.3.3 Functions. To handle all matters relating to regulations (including special permits for waiver or exemption) issued under Title 18 U.S.C. 831-835; Section 9, Department of Transportation Act, 49 U.S.C. 1657; and Title VI and section 902(h) of the Federal Aviation Act of 1958, 49 U.S.C. 1421—1430, 1474(h), for the shipment and transportation of hazardous materials.

6-3.3.4 Publication of Regulations. Regulations, other than special permits, developed by the Board for the shipment and transportation of hazardous materials will be published in the FEDERAL REGISTER and in the Code of Federal Regulations. To the extent practicable these regulations will be the same for all modes of transportation, will be adopted under the same procedures, and will be published in the same document or series of documents. Regulations now contained in Parts 171—190 of Title 49 CFR and in Part 103 of Title 14 CFR will henceforth be designated as the "Hazardous Materials Regulations of the Department of Transportation."

6-3.3.4.1 Designation of a Chapter for Hazardous Materials Regulations. On December 18, 1968 the Secretary of Transportation amended Subtitle B of Title 49 CFR of the CFR by adding a new Chapter 1 to include Parts 100 through 199 to be entitled, "Chapter I, Department of Transportation; Hazardous Materials Regulations Board" which will contain the Hazardous Materials Regulations. This establishment does not affect the regulations presently contained in Parts 170 through 190 of Title 49 CFR.

6-3.3.5 Communications with the HMRB. All communications with the Board should be addressed to the Secretary, Hazardous Materials Regulations Board, Department of Transportation, 400 Sixth Street, S.W., Washington, D.C. 20590.

6-3.3.6 Identification of HMRB Regulatory Actions. All such actions promulgated by the HMRB will have Docket numbers preceded by "HM" (e.g., Docket No. HM-7; Notice No. 68-5).

6-3.3.7 Rule-Making Procedures of the HMRB. The procedures are set forth in Docket No. HM-1, (reference 1) issued on May 22, 1968, which amended Part 170 to Title 49 CFR for the specific purpose. The following portions are excerpted from that document because they describe how hazardous materials rule making previously was handled and the transition of these activities into the DoT organization.

6-3.3.7.1 Historical Background. The shipment and carriage of hazardous materials by carriers subject to the Interstate Commerce Act (rail, motor carrier, pipeline, inland waterway) is governed by sections 831—835 of Title 18, United States Code. Before April 1, 1967, this authority was exercised by the Interstate Commerce Commission. Since that date, the authority has been exercised by the DoT, pursuant to the Department of Transportation Act. The shipment and carriage of hazardous materials by air has since 1958 been governed by section 902(h) of the Federal Aviation Act of 1958, which authorizes the Federal Aviation Administrator to issue his own regulations or to adopt, in whole or in part, the regulations issued under Title 18 U.S.C. by the Interstate Commerce Commission (ICC). The FAA has, in the past, for the most part adopted the regulations issued by the ICC. The shipment and carriage of hazardous materials by vessel is governed by section 4472 of the Revised Statutes (46 U.S.C. 170) which authorizes the Commandant of the Coast Guard to define, describe, name and classify hazardous materials and establish regulations for their carriage. It also requires him to "accept and adopt" for these purposes, the ICC regulations so far as they apply to shippers by common carriers by water. Thus the vast majority of the regulations applicable to hazardous materials were those adopted by the ICC in Title 49 of the CFR's.

Within the ICC, the rule-making authority with respect to hazardous materials was delegated to an employee board of the Commission called the Explosives and Other Dangerous Articles Board. This Board issued the notices, evaluated the comments and adopted final amendments for the Commission.

Upon establishment of the Department of Transportation, effective April 1, 1967, the powers and duties of the ICC, FAA and Coast Guard, as described in Docket No. HM-1, with respect to the transportation of hazardous materials were transferred to DoT, then to the HMRB. (Reference 1)

6-3.3.7.2 Existing Procedures. The following indicates the principal aspects of the rule-making procedures, where they may be found and the authority behind them:

Subpart A-General

Sec.

170.1 Applicability.
170.3 Initiation of rule making.
170.5 Participation in rule-making proceedings.
170.7 Regulatory docket.

Subpart B-Petition for Rule Making

170.11 Filing of petitions for rule making.
170.13 Filing of petitions for special permits for waivers and exemptions.
170.15 Processing of petitions for rule making and special permits.

Subpart C-Procedures

170.21 General.
170.23 Contents of notices.
170.25 Petitions for extension of time to comment.
170.27 Consideration of comments received.
170.29 Additional rule-making proceedings.
170.31 Hearings.
170.33 Adoption of final rules.
170.35 Petition for rehearing or reconsideration of rule.

AUTHORITY: The provisions of this Part 170 issued under Title 18 U.S.C. sec. 831-835; sec. 9, Department of Transportation Act (40 U.S.C. 1657); Title VI and sec. 902(h), Federal Aviation Act of 1958 (49 U.S.C. 1421—1430, 1472(h).

6-3.3.8 HMRB Philosophy and Areas of Contemplated Rulemaking. The following information, excerpted (with minor modifications for updating) from Docket No. HM-7; Notice No. 68-5 issued August 16, 1968, (reference 2) is included as an alert (NOTE: These are not regulations) because of the anticipated significant impact such activity will have on chemical rocket/propellant operations and because the logical approach and ideas expressed should assist in safety program development in the interim as well as stimulating support for accomplishing these changes.

6-3.3.8.1 Background. The existing regulations reflect a commodity-by-commodity and package-by-package approach. As a result, the regulations focus on commodities instead of hazards. For example, (i) the present classification of hazards does not identify spontaneous combustion and (ii) excepting class A poisons and radioactive materials, only one classification (the greatest hazard) may be identified, even though the material may present more than one serious hazard. As another result, the packaging regulations are repetitious how-to-do-it instructions, rather than general performance standards. For example, Part 178—Shipping Container Specifications consists almost entirely of specifications and tests for individual packages already developed; it does not set standards for the development of new packages. Recent regulatory actions have sought to synthesize the specifics, but the bulk of the regulations still deal in details.

Different authorities developed the safety regulations for air, land, and water modes of transportation. As a result, the hazardous materials regulations differ in many particulars between the modes; some differences are of form, others of substance. The differences impose burdens on shippers and carriers in inter-modal shipments. One of the functions of the HMR is to make the regulations uniform, to the extent that uniformity is consistent with the differences inherent in the modes.

6-3.3.8.2 Scope. The HMRB plans to issue notices of proposed rule making in at least these areas:

Classification and Labels
Handling and Stowing
Placards and Emergency Procedures
Packages.

The Board's initial emphasis will be on inter-modal shipments of packaged materials, but the classification, placards and emergency procedures notices will also cover shipments by portable tank, tank car, tank truck drums, and cylinders. The Board does not have jurisdiction over bulk shipments of hazardous materials by water under Title 46—Shipping. See Section 6-5.1.2.8.

6-3.3.8.3 Uniformity. The regulations should be uniform for all modes of transportation, differing only where the inherent characteristics of an individual mode require a difference. The regulations should be consistent with international standards, differing only where our national needs require a difference.

6-3.3.8.4 Classification and Labels. Classification should be based upon the transportation of materials for which varying degrees of hazard must be provided. Materials which pose a similar threat to safety should be classed together, without regard to historic classification. Labels should (i) give notice of the hazard potential of the material in the package and (ii) call attention to the need for special handling and stowing. See section 6-4, United Nations Labeling Criteria for additional proposed HMRB actions.

6-3.3.8.5 Handling and Stowing. Instructions for in-transit handling should be on the label and should be written so that all persons involved can understand and apply them. Additionally, one might have a simple color-code scheme for separating incompatible materials. Since many thousands of people, of varying levels of competence and training, are involved in in-transit handling, there will be some difficulty in finding the proper balance between flexibility (which increases complexity) and simplicity.

6-3.3.8.6 Placards and Emergency Procedures. Placards required to be posted on portable tank, tank cars, tank motor vehicles, transport vehicles and containers should parallel the label requirement. Placards should (i) give notice of the hazard potential of the material being transported, (ii) call attention to the need for special treatment by the carrier, and (iii) give notice of the need for special care after an accident. Since many thousands of people (cargo handlers, longshoremen, policemen, firemen, ambulance attendants) are concerned with handling emergencies involving hazardous materials, some means should be devised for giving these persons instructions on handling these emergencies. This could be done by putting code numbers on the placards and distributing booklets with emergency instructions keyed to these code numbers.

6-3.3.8.7 Packaging. Packaging requirements should relate to the classification, the quantity of material involved and the transportation environment. Packaging requirements should be stated in terms of performance standards, when possible. Performance standards should be used as a means of measuring newly developed packaging systems and should not replace manufacturing specifications for proven packaging systems. The regulations should prescribe tests to determine whether the packages meet the requirements.

6-3.3.8.8 Petitition for Special Permit. (See also 6-5.1.2.9 and its subparagraphs which deal especially with military shipments.) This information has been excerpted from Docket No. HM-1, issued May 22, 1968, (reference 1) and Docket No. HM-12 (reference 3); Notice No. 68-9, issued January 13, 1969.

6-3.3.8.8.1 Categories of Special Permits.

a. Permits for one-of-a-kind, emergency on military shipments

b. Experimental or developmental permits, which develop information for future regulatory action

c. General interest permits, which are based on existing knowledge.

6-3.3.8.8.2 Special Permit. A Special Permit is a special regulation, a waiver or exemption from some provision of the general regulations. A petition for a special permit is usually evaluated on the basis of information submitted with the petition (49 CFR 170.13) without the benefit of public comment.

6-3.3.8.8.3 Filing of Petitions for Special Permits. (Reference 1, 170.13)

a. Any person may petition the Board for a special permit for a waiver or exemption from any provision of Parts 171-190 of this chapter or Part 103 of Title 14 (14 CFR Part 103).

b. Each petition must be submitted in duplicate to the Secretary, Hazardous Materials Regulations Board, Department of Transportation, 400 Sixth Street, S. W., Washington, D. C. 20590, and contain the following information:

(1) The regulatory provisions involved.

(2) The justification for the permit, including any reasons why the regulations are not appropriate, why the public interest would be served by the proposal, and the basis upon which the proposal would provide an adequate and reasonable degree of safety.

(3) A detailed description of the proposal, including when appropriate, drawings, plans, calculations, procedures, test results, previous approvals or permits, a list of specification containers, if any, to be used, a list of modified specification containers, if any, to be used, a description of the modifications, and any other supporting information.

(4) The chemical name, common name, hazard classification, form, quantity, properties, and characteristics of the material covered by the proposal, including composition and percentage (specified by volume or weight) of each chemical, if a solution or mixture.

(5) Any relevant shipping or accident experience with the container proposed.

(6) The proposed mode of transportation, and any special transportation controls needed.

(7) The name, address, and telephone number of the petitioner, and that of the motor carrier if a tank motor vehicle is to be used.

(8) A statement or recommendation regarding any changes to the regulations which would be desirable to obviate the need for similar special permits.

c. Unless there is good reason for priority treatment, each petition is considered in the order in which it is received. To permit timely consideration, petitions should be submitted at least 45 days before the requested effective date.

6-3.3.8.8.4 Processing of Petitions for Special Permits. (Reference 1, 170.15)

a. General: The Board considers the information submitted by the petitioner and any other available pertinent information. Unless otherwise directed by the Board, no public hearing, argument, or other proceeding is held directly on a petition before its disposition.

b. Grants: If the Board finds that the petitioner's proposal would provide adequate safety and is otherwise justified, the Board issues the special permit under this subpart or initiates rule-making action under Subpart C of this part.

c. Denials: If the Board finds the petitioner's proposal would not provide adequate safety or is not otherwise justified, the Board denies the petition. The Board will inform the petitioner of the basis for the denial.

d. The treatment of confidential or proprietary material submitted by any petitioner is governed by Section 7.59 of this title.

6-3.3.8.8.5 Issuance of Special Permits. The Department issues a special permit when it appears that the waiver or exemption will be in the public interest and will result in an appropriate level of safety. Special permits can be issued more quickly than the regulations can be amended under normal procedures. A special permit is usually issued to a single company or government agency, giving them the right to do something which the regulations normally prohibit. The same waiver or exemption may be granted to the other companies upon petition.

6-3.3.8.8.6 General Interest Permits. Once the first petition has been evaluated and the permit issued, the Department routinely issues subsequent General Interest Permits to similarly situated companies. A general interest permit, when issued to all similarly situated companies, is really a disguised amendment to the regulations. The Department may also treat as requests for rule making those petitions for special permits which are clearly within the general interest class. If a petition is without merit, the Department will deny it. If a petition appears to have merit, the Department may issue a notice of proposed rule making, usually with a 30-day comment period, and then, after evaluating the comments, either amend the regulations or deny the petition.

Special permits for experimental, developmental, one-of-a-kind, emergency, and military shipments, would continue to be issued under present procedures. Special permits for radioactive materials and for cryogenic liquefied gases would also be handled under the present procedure for the time being.

6-3.3.8.8.7 Forwarding of Petition for Special Permits. Petitions for Special and General Interest Permits from industry and government agencies (other than the Department of Defense (DoD)) should be forwarded with substantiating evidence to the: Secretary, Hazardous Materials Regulations Board, Department of Transportation, Washington, D. C. 20590. Request for Special and General Interest Permits from DoD components should be forwarded to the Military Traffic Management and Terminal Service (MTMTS) which acts as the DoD point of contact with the DoT.

6-3.4 CHANGE OF REFERENCE FROM ICC TO DOT. The purpose of Docket No. HM-11 (Amendments 171-2, 173-4, 174-2, 175-2, 176-1, 177-4, 178-2, 179-1, 180-1), issued November 27, 1968 (reference 4), was to convert certain references in the Hazardous Materials Regulations from "Interstate Commerce Commission" to "Department of Transportation" respectively and "ICC" to "DoT" while permitting continued use of "ICC" as a specification marking on newly manufactured packagings for a reasonable period of time. The following is excerpted therefrom:

a. The Hazardous Materials Regulations (49 CFR Parts 170–190) refer in many places to the use of "ICC" in specification markings. Since conversion from "ICC" to "DoT" on newly manufactured packagings would require the changing of numerous marking devices, it is reasonable to authorize the use of either "ICC" or "DoT" as markings on newly manufactured packagings for an additional period of time. Under this amendment, either marking could be used until January 1, 1970. On and after that date all newly manufactured packagings must be marked "DoT" as required. However, packagings with the previously required ICC specification markings which are manufactured before January 1, 1970, may be continued in service as marked.

b. By striking out the words, "Interstate Commerce Commission" and "Commission" wherever they appear in Parts 171 through 180 and by inserting the words "Department of Transportation" and "Department" respectively in place thereof.

c. By striking out the letters "ICC" wherever they appear in Parts 171, 173, 174, and 177 through 179 and by inserting the letters "DoT" in place thereof except in the following sections: 173.23(b), 173.32(b), (b) (3), (c), and (d); 173.33(e) (1); 173.34(e) (10) in the table each cylinder to which footnote one applies: 173.124(a) (5) each specification to which footnote one applies; 173.301(h) in the table each cylinder to which footnote one applies; 173.304(d) (3) (ii) in the table each container to which footnote one applies; and in 173.314(c) in the table each tank car to which footnote one applies.

d. Part 171 has been amended to add a new Section 171.14 as follows: 171.14 Specification markings. (a) Notwithstanding any other requirements of Parts 171 through 179 of this chapter, the letters "ICC" were permitted to be placed on any packaging requiring specification marking until January 1, 1970. (See Section 6-3.4) (b) Packagings with the specification markings "ICC" placed thereon before January 1, 1970, may be continued in service as marked. (See Section 6-3.4)

6-4 UNITED NATIONS LABELING CRITERIA

The following, excerpted from Docket No. HM-8, issued October 9, 1968 (reference 5), indicates one area of emphasis of the HMRB and introduces the United Nations Hazardous Materials Labeling System which was developed by the United Nations Committee of Experts on the Transport of Dangerous Goods. (The U.N. classes have not been adopted by the HMRB.)

6-4.1 RECOMMENDED LABELING SYSTEM OF UNITED NATIONS COMMITTEE OF EXPERTS ON THE TRANSPORT OF DANGEROUS GOODS.

a. The United Nations labels are color-coded and identify each kind of hazard with a pictorial symbol and classification number.

b. Each label represents a class of hazard.

c. When one label does not represent all of the serious hazards presented by a material, the U.N. System provides for the additional hazards to be represented by additional labels without the class number.

6-4.2 DOCUMENT AVAILABILITY. This document may be purchased from: United Nations Sales Section, New York, N.Y. Order by this title: Transport of Dangerous Goods (1966). ST/ECA/81/Rev. 1, E/CN.2/Conf. 5/10 Rev. 1, Sales No. 1967 VIII 2. Ask for latest revision.

6-5 DEPARTMENT OF DEFENSE REGULATIONS FOR CONTRACTORS TRANSPORTING AMMUNITION, EXPLOSIVES, AND RELATED DANGEROUS MATERIALS

Because an extensive amount of work is performed by contractors for the various elements of the Department of Defense and other Government Departments and Agencies, mention is being made in detail of a portion of DoD 4145.26M, October 1968, because of its relevance to the subject. NOTE: Other Government organizations may use all, part or none of the requirements set forth in the DoD document, so it is essential that contractors and all those concerned with contractor transport of hazardous materials be completely familiar with the specifications set forth in the specific contractural documents of concern regarding hazardous materials transportation and shipment, and understand in their entirety all pertinent regulations.

6-5.1 DOD CONTRACTORS' SAFETY MANUAL FOR AMMUNITION, EXPLOSIVES, AND RELATED DANGEROUS MATERIALS (DoD 4145.26M), dated October 1968, DoD Office of Assistant Secretary for Defense (Installations & Logistics). This document is discussed because it provides good guidance and insight into the criteria aspects. Some additional information is inserted and/or modifications are made in places.

6-5.1.1 General. The Foreword to this document (4145.26M) states that it is issued under the authority of and in accordance with the Department of Defense Instruction 4145.26, subject: DoD Contractors' Safety Manual for Ammunition, Explosives, and Related Dangerous Materials, dated June 21, 1968. It provides uniform safety practices to be used in industrial plants and facilities by contractors involved with contracts for ammunition, explosives and related dangerous material of the DoD, Military Departments, and Defense Agencies (hereinafter referred to collectively as "DoD Components") or other activities as specified in the contract.

This manual is a compilation of safe practices and standards used by DoD Components and other recognized national agencies. Questions on interpretation and recommendations for amendments to this Manual should be submitted to the Cognizant DoD Components through the procuring contract officer as appropriate.

Attention is called to Part 1—Introduction, because it sets forth responsibilities; Part 2—Explanation of Terms. Dangerous Material is defined as "all material, including ammunition and explosives, such as flammable liquids and/or solids, oxidizing materials, corrosive liquids, compressed gases, poisons, and radioactive material;" and Part 13—Transportation and Intraplant Movement of Ammunition, Explosives and Related Dangerous Material (AEDM). The entire chapter should be read.

6-5.1.2 Chapter 13—Transportation and Intraplant Movement of Ammunition, Explosives and Related Dangerous Material (AEDM). A major portion of this chapter is found in the succeeding subparagraphs. The fact that portions have been omitted for brevity does not imply that they are not significant or important.

6-5.1.2.1 General. The purpose of this part is to prescribe safety standards for providing preparation and shipment of ammunition, explosives, and related dangerous material. These standards are for the guidance of personnel engaged in these activities and are in addition to those regulations promulgated by authorized agencies. See also Section 6-5.2.

6-5.1.2.2 National Standards. As prescribed in the Code of Federal Regulation (CFR Title 49, Transportation, CFR Title 14—Aeronautics and Space, and CFR Table 46—Shipping), the regulations promulgated by the Department of Transportation (DoT) are mandatory and constitute minimum requirements for the transportation of AEDM by all modes of transportation. In certain cases, requirements of the National Standards may have to be exceeded because of material characteristics and operational hazards. In such case, all standards of this part will apply.

6-5.1.2.3 Methods of Transportation.

6-5.1.2.3.1 Allowable. AEDM may be transported by any one or a combination of the following methods:

a. Rail

b. Water (ships, barges, lighters, boats, etc.)

c. Motor truck

d. Aircraft (nonpassenger).

6-5.1.2.3.2 Prohibited. In no case will AEDM be shipped by the following methods:

a. Mail or parcel post

b. Privately owned passenger vehicles

c. Passenger-carrying vehicles except as allowed by DoT regulations.

6-5.1.2.4 Preparation of AEDM for Shipment. All AEDM shall be packaged and marked for shipment in accordance with contract specifications.

6-5.1.2.5 Railroad Transportation. The DoT Regulations are minimum requirements for commercial and government-owned railcars for intraplant and commercial rail operations. Methods of blocking, bracing, and staying of AEDM are contained in Bureau of Explosives Pamphlets 6 and 6A. These methods may be supplemented by contract specifications. In addition to the above, the standards of this paragraph as applicable shall be observed.

6-5.1.2.6 Motor Vehicle Transportation. The operation of motor vehicles shall be in accordance with Federal, State, and local requirements. A locally developed motor vehicle program for intraplant operation should, in addition to effective administration, include such necessities as accident reporting, records, warning signs, road-parking and pedestrian traffic layouts, driver training, and enforcement.

6-5.1.2.7 Air Transportation. Air transportation of AEDM by commercial aircraft is regulated by DoT Regulations, promulgated by the Federal Aviation Administration (FAA). Instructions pertaining to AEDM laden military aircraft and certain DoD contract airlift operations conducted under FAA waiver are contained in AFM 71-4, DSAM 4145.3, TM 38-250, NAVWEPS 15-03-500 or MCO P4030.19, "Packaging and Handling of Dangerous Materials for Transportation by Military Aircraft." When safe standards or criteria referenced above vary with this manual, the standards promulgated herein shall apply. DD Form 836-1, "Instructions for Aircraft Commander Transporting Explosives or Other Dangerous Articles by Military or Civilian Aircraft," shall be utilized as prescribed by DSAR 4500.3, AR 55-355, AFM 75-2, MCO P4600.14 or NAVSUP PUB 444.

6-5.1.2.8 Water Transportation. Transportation of AEDM as cargo by water is governed by U. S. Coast Guard publications entitled "Rules and Regulations for Military Explosives" (USCG 108), "Explosives or Other Dangerous Articles on Board Vessels" (USCG 187), and the provisions of this manual. (Reference 6)

6-5.1.2.9 Special Permits.

6-5.1.2.9.1 General. Regulations of the Department of Transportation governing the safe surface transport of ammunition, explosives, and other dangerous articles are binding upon all shippers and all common, contract, and private land carriers who transport AEDM in interstate commerce. However, situations may arise wherein it may not be feasible to comply with DoT regulations, or proposed shipments may include materials not covered by existing regulations. In such cases, special permits shall be requested. (See 6-3.3.8.8 and its subparagraphs for more information on special permits.)

6-5.1.2.9.2 Procedure for Obtaining Special Permits. Upon determining that existing DoT regulations are not applicable to a proposed shipment, the shipping activity shall advise, through the procuring activity, the Contracting Office of the need for a special permit. All military shipments must be coordinated through Military Traffic Management and Terminal Service (MTMTS).

Requests for special permits must include the following information, as applicable:

a. Complete description of the commodity, including its hazard classification

b. Reports of tests conducted to determine the hazard classification when the commodity is not covered by DoT regulations governing the safe transportation of AEDM

c. Origin and destination of the shipment

d. Type of packaging and packing

e. Supporting information indicating that the proposed shipment is safe for transportation

f. Justification for requesting a special permit, citing specific regulations from which the exemption is required

g. The estimated total weight of the shipment(s)

h. The period of time for which the special permit will be required

i. Anticipated shipping date(s)

j. Mode(s) of transportation required.

6-5.1.2.9.3 Renewals of Special Permit. When it becomes apparent that a shipment for which a special permit has been issued will not be completed before the expiration date, a request for extension shall be submitted. This request must be submitted to DoT at least 45 days prior to the expiration date of the permit. All such requests must include the contemplated date(s) of the completion of the shipment(s).

6-5.1.2.9.4 Exemption of Classified Shipments from Carrier Inspection. DoT Special Permit No. 868 exempts the Military Departments from inspection by rail or motor carriers of the lading and staying of classified AEDM shipments. This permit further exempts the Military Departments from inspection by the carrier or representative of the Bureau of Explosives of the methods of manufacture, packing and storage, or lading and staying.

6-5.1.2.10 Materials Handling Equipment. Specifications, operations, and maintenance of materials handling equipment shall conform with the requirements of TM 743-200, NAVSANDA PUB 284, AFM 67-3, NAVMC 1101, DSAM 4145.1, USAS B56.1 1959, National Fire Codes, and other standards contained in following data sources. When the above-referenced publications vary with the requirements, then those in the parent document take precedence.

6-5.2 DOD EXPLOSIVES HAZARD CLASSIFICATION PROCEDURES. (Reference 7) It was proposed that new military AEDM be exempt from Bureau of Explosives and subject to TB-700-2 of May 1967 (reference 8). Further clarification of this point was HM-3 amendment (reference 9). Section 173.86 was amended with respect to the DoD approval of the classification when tested by the Hazards Classification Procedure rather than referencing the specific document TB-700-2. It is understood that this is the procedure used by DoD elements.

6-5.3 DATA SOURCES

Department of Defense	
DoD Directive 4145.18	Quantity-Distance Standards for Pier and Wharf Facilities Handling Explosives and Ammunition
DoD Instruction 4145.21	Quantity-Distance Standards for Liquid Propellants
DoD Instruction 4145.22	Quantity Limitations and Quantity-Distance Standards for Manufacturing, Handling, and Storing Ammunition and Explosives
DoD Instruction 4145.23	Quantity-Distance Standards for Manufacturing, Handling, and Storage of Mass-Detonating Explosives and Ammunition
DoD Instruction 4145.24	Determination of Ammunition and Explosive Characteristics which Influence Handling, Storage, and Transportation Criteria
DoD Instruction 4145.25	Quantity Distance Standards and Policies for Airfields, Heliports, and Seadromes
DoD Instruction 4145.26	DoD Contractors' Safety Manual for Ammunition, Explosives, and Related Dangerous Material
DoD Manual 4145.26M	Contractors' Safety Manual for Ammunition, Explosives, and Related Dangerous Material
DoD Directive 4145.27	DoD Safety Standards for Ammunition and Explosives
DoD Manual 4145.27M	DoD Safety Standards for Ammunition and Explosives
Office of the Director of Defense Research and Engineering	The Handling and Storage of Liquid Propellants
Department of the Air Force	
AFM 127-100	Explosives Safety Manual
T.O. 11C-1-6C	General Safety Precautions for Missile Liquid Propellants
T.O. 11A-1-42	General Instructions for Disposal of Ammunition
Department of the Army	
TM 9-1300-206	Care Handling, Preservation, and Destruction of Ammunition
Headquarters, U. S. Army Materiel Command	
AMCR 385-224	AMC Safety Manual
AMCR 385-225	Safety Requirements for Manufacturing and Processing Military Pyrotechnics
AMCR 385-226	Safety Requirements for Manufacturing Nitroglycerin
AMCR 385-227	Safety Requirements for Manufacturing Double-Base Solventless Propellants
AMCR 385-228	Safety Requirements for Manufacturing Small Arms Ammunition
AMCR 385-229	Safety Requirements for the Manufacturing of Single Base Solid Propellants
AMCR 385-230	Safety Requirements for the Manufacturing and Loading of Castable Composite Propellants

Department of the Navy

NAVWEPS Ordnance Pamphlet 5	Ammunition Ashore—Handling, Stowing, and Shipping
NAVWEPS Ordnance Pamphlet 2165	Navy Ordnance Shipping Handbook
NAVSO P-2455	Department of the Navy Safety Precautions for Shore Activities
NAVDOCKS P-300	Management of Transportation Equipment
NAVDOCKS P-342	Fuel Storage Tank Cleaning at the Shore Establishment
NAVEXOS P-422	Navy Manual of Safety Equipment

Defense Supply Agency

DSAM 8220.1	Specialized Safety and Flight Operations Manual for Contract Administration Services

Multi-Service

AFM 71-4, TM 38-250, NAVWEPS 15-03-500, and MCO P4030.19	Packaging and Handling of Dangerous Materials for Transportation by Military Aircraft
DSAR 4500.3, AR 55-355, AFM 75-2, NAV SUPPUB 44, and MCO P4600.14.	Military Traffic Management Regulation

6-6 REFERENCES

1. DoT, HM-1, "Rule-making Procedures of the Hazardous Materials Regulations Board," Federal Register, Vol. 33, No. 108, 4 June 1968.
2. DoT, HM-7, "Transportation of Hazardous Materials—Notice of Plan to Revise Regulations," Federal Register, Vol. 33, No. 163, 21 August 1968.
3. DoT, HM-12, "Transportation of Hazardous Materials—First Public Notice on a Petition for Special Permit," Federal Register, Vol. 34, No. 16, 24 January 1969.
4. DoT, HM-11, "Change of Reference from ICC to DoT," Federal Register, Vol. 33, No. 234, 3 December 1968.
5. DoT, HM-8, "Transportation of Hazardous Materials—Request for Public Advice on Labels and Classification," Federal Register, Vol. 33, No. 202, 16 October 1968.
6. DoT, USCG "Transportation or Storage of Explosives or Other Dangerous Articles or Substances, and Combustible Liquids on Board Vessels," Title 46 CFR, Part 146, latest revision and amdts.
7. DoT, HM-3, "Explosives and Other Dangerous Articles—Notice of Proposed Rule-making," Federal Register, Vol. 33, No. 39, 27 February 1968.
8. DoD 4145.27 "Explosives Hazard Classification Procedures," (TB 700-2, NAVORDINST 8020.3, TO 11A-1-47, DSAR 8220.1) 19 May 1967
9. DoT, HM-3; Amdt. 173-6, "Miscellaneous Amendments to Chapter 1," Federal Register, Vol. 34, No. 83, 1 May 1969.

CHAPTER 7

ACOUSTIC ENERGY HAZARDS

7-1 INTRODUCTION

Airborne acoustic energy fields at certain intensity levels interfere with man's work-activities or his routines of daily living. Depending on the actual energy level and other characteristics of these acoustic energy fields, man experiences bodily injury, damage to his hearing organs, reduced performance capability on his job, reduced ability to carry on necessary or desired conversations or the induction of annoyance with and resentment of the energy sources and their operators. All these undesired human experiences are called "environmental hazards of acoustic energy." Chemical rocket propulsion systems generate acoustic energy at levels great enough to induce some or all of the hazards just cited. Therefore, these acoustic energy fields are to be defined, described physically, and related to the hazards they create for the men who work or live within their borders. Assessments of the effects of the acoustic energy fields generated by chemical rocket propulsion systems, will be stated in terms of acoustic hazards criteria, to provide a data base by which one may specify the actual human hazard created by each system. These criteria data are the foundations for the planning, the operational control, and/or the specific design of equipment and facilities that can assure adequate protection for personnel working with or living near the acoustic energy sources, that is, the propulsion systems. Of course these acoustic energy fields may damage the missile, the space vehicle or the supporting facilities, but here a primary concern for hazards to man precludes consideration of their effects on structures, except to the extent that the sound wave-induced responses of the structures also create secondary hazards for man.

The release, into the surrounding environment, of large amounts of acoustic energy (intense sound waves) always attends the operation of chemical rocket propulsion systems, especially those of large space vehicles. This airborne sound (noise) field is generated during the normal static (restrained) or launch operation of the propulsion system. The acoustic energy propagates through air and creates energy fields of varying levels throughout extended environmental areas surrounding the system and wherever these energy levels exceed certain limiting values, the men working there are subjected to acoustic energy hazards.

The acoustic energy fields in the vicinity of operational chemical rocket propulsion systems may be measured. Frequently there is urgent need for information about the acoustic energy fields generated by projected systems. These needs may be satisfied by estimating the acoustic energy output of these future systems by applying prediction methods that have been developed over the past several years. Measurement and prediction methods are presented herein but emphasis is placed on the prediction methods which also include consideration of the effects of the propagation medium (air) in reducing or enhancing the propagated acoustic field strength. Several commonly encountered acoustic energy environments are illustrated and the several acoustic energy hazards criteria applicable to man are stated. Environmental acoustic energy fields (measured and predicted) are described and compared with the acoustic energy hazards criteria. From these comparisons and assessments, planning is described in relation to the effects of acoustic energy on man and in relation to its effects on site selection, facility lay-out, land use and personnel protection.

The intense acoustic environments generated by the propulsion systems of large space vehicles are acknowledged hazards which must be considered for restrained (static test and pre-launch conditions) firing and flight operations of these vehicles. These environments influence every aspect of space vehicle design, development, and operation. The space vehicle structure, electronic components, subsystems, and flight crew must be safeguarded against the above environments. These same safety considerations must also apply to ground support structure, equipment, personnel, as well as civilian communities surrounding static test firing and launching sites, remembering that as rockets grow in size, the magnitude and complexities of the problem grow proportionately.

Prediction of the magnitude and characteristics of the acoustic environments offers great challenges in tempering and applying basic rigorous scientific principles to engineering problems. The physical phenomena have the problem of inadequate theoretical foundations from a practical standpoint. Since theoretical approaches involve nonlinear relationships, they are extremely complex, and in most cases lack detailed experimental data to guide, improve and strengthen the theories. Because of this inadequate theoretical foundation, analytical and empirical models, based on dynamic similarity principles, have been developed for arriving at engineering estimates of the acoustic environments of large space vehicles. These empirical models are based on available experimental data from full-scale and dynamically-scaled model test data. When faced with the problem of applying the analytical or empirical prediction models to a proposed space vehicle configuration, their inherent limitations must be understood. The resulting environmental estimates are therefore engineering estimates and should not be treated as exacting scientifically accurate answers. On the other hand, when used correctly, these models will provide adequate engineering answers for the bases of design, development and hazards criteria. Typical examples of estimated environments will be presented.

Since the prediction models are based on the assumption of a homogeneous, isotropic, isentropic propagation medium, another section will briefly present remarks on the effects of the atmospheric propagational medium with respect to the propagation of sound. Suppression of the noise generated by rocket engines is summarized last.

7-2 AIRBORNE SOUND WAVE ENVIRONMENTS

7-2.1 PREDICTION TECHNIQUES. All aspects of the acoustic environment generated by rocket propulsion systems should be defined at the earliest possible time during the research, development, and operational cycle of a given space vehicle system. Therefore, methods must be available to estimate the acoustic environmental characteristics in the various surrounding regions which are influenced by the operational aspects of both static firing and the actual launch of the vehicle (see bibliography). The regions subjected to the intense acoustic noise are the vehicle itself, the structures, facilities, and personnel in the immediate area, as well as the surrounding communities.

The regions surrounding the static or launch site fall into basically three areas: the near-, mid-, and far-field. In the acoustic near-field, the geometric spatial extent of the exhaust flow considered as a source and the nonradiating components of the fluctuating pressure field must be considered, i.e., for distances within a wave length or so. In the acoustic mid-field, the geometric spatial distribution of the exhaust flow as a source, as well as its radiation (directivity) characteristics, must be considered; however, all pressures are radiated acoustic pressures, e.g., for distances of three to five wave lengths. In the acoustic far-field, all acoustic pressures seem to originate from a point source, e.g., for distances of at least ten wave lengths. Prediction of the acoustic environments for the near-, mid-, and far-field requires the use of different analytical/empirical models due to their various physical characteristics. For example, in the near- and mid-field areas, the near-field terms and the spatial distribution of sound sources must be included; these are important because of their dominating influence at the observation point. In the far-field, the distribution of apparent sources is of no importance because the directivity and point source power characteristics are sufficient to predict the environment. The particular source-receiver relationship dictates which prediction model must be used. At present a universal model is not available, in a practical sense, for predicting in all areas.

The theoretical description of the acoustic field radiated by a jet flow was initially formulated by Lighthill (reference 1). This is the now famous "acoustic analogy" approach. Since then, other approaches to the noise field of jets have been performed by Phillips (reference 2), Williams (reference 3), Ribner (reference 4), and Peters (reference 5). A concise historical background of the developments of jet noise theory is given in reference 6. These theories of jet noise are extremely complex, and as yet, only qualitative information can be inferred from them. Using the notation of reference 7, the theoretical wave equation for acoustic motions (assuming linear approximations) can be written most generally as:

$$\Box^2 P \equiv \nabla^2 P - ((1/C_o^2)(\partial^2 P/\partial t^2)) = (-\partial Q/\partial t) + (\nabla \cdot \vec{F}) - ((\partial^2(\rho \vec{q}_i \vec{q}_k - \tau_{ik})/(\partial x_j \partial x_k)) - ((\partial^2/\partial t^2(P/C_o^2 - \rho)). \quad \text{(Eq. 7-1)}$$

The right-hand terms will vanish in a source-free, homogenous, isentropic medium at rest, while far from the source. In the confined region where the violent exhaust flow exists, they become appreciable and may be regarded as sound sources. Such a representation provides some insight about the mechanisms of sound generation; the following definitions are shown as examples.

$\partial Q/\partial t$	An unsteady injection of fluid (i.e., pulsating mass flow through the nozzle exit area, etc.)—monopole type radiation.
$\nabla \cdot \vec{F}$	Spatial variation of body force (i.e., can represent pulsating thrust force across nozzle exit)—dipole type radiation.
$\partial^2/\partial x_j \partial x_k (\rho \vec{q}_i \vec{q}_k)$	Sound generation due to momentum fluctuations, including the Reynolds stress. This term is a major noise source in turbulent flow and turbulent jets—quadrapole radiation.
$\partial^2/\partial x_i \partial x_k (\tau_{ik})$	Sound generation due to fluctuations of viscous stresses, generally negligible.
$\partial^2/\partial t^2((P/C_o^2) - \rho)$	The effect of entropy fluctuation, temperature fluctuations. This term can be monopole or quadrapole in nature, depending on the influence of convection properties of flow.

The relative importance of these terms to the noise field generated by hot rocket exhaust flow fields is the subject of much debate, and much effort is being expended to determine their relative contributions. Because of the lack of detailed knowledge of these source quantities, the radiated acoustic field of even a free (undeflected) hot rocket exhaust by the purely theoretical approach cannot be estimated at this time.

Since a complete solution to the theoretical description of jet noise does not exist, techniques now being used to predict the acoustic environments of rocket exhaust flows are, by necessity, based on analytical/empirical models. These models depend upon the principles of dynamic similarity because dynamically similar flows produce similar acoustic characteristics. Deflecting the flow, as is done for most launch and static firing conditions, further complicates the theoretical considerations, and solutions are even more untractable. The prediction models are thus developed from sets of dynamically similar full-scale and model experimental data. For most of the above regions, prediction techniques have been developed which can be used to obtain "engineering estimates" of the acoustic environments created by the booster stages of a vehicle system. The engineering estimates usually consist of the overall sound pressure level, OA SPL and its spectral decomposition (i.e., OB SPL, etc.) at a given observation point.

7-2.1.1 Near-Field Environments. In the acoustic near-field of a hot supersonic rocket the exhaust stream appears as a spatially extended region which generates fluctuating pressure fields with components that do not radiate to the far-field. The basic noise generation mechanisms in the near-field are not well defined and the fluctuating energy in the near-field is of such magnitude that nonlinear acoustics is of importance. The insertion of a deflector complicates the source description even more. Currently, there is a lack of sufficient experimental information available to properly define or describe the source and its resulting field characteristics for use in a near-field prediction model. A contributing factor to this deficiency (i.e., the severe lack of good data) is that it is extremely difficult to obtain without special equipment because of the high velocity and elevated temperatures. Thus, a generalized technique has not been developed for predictions which can estimate the extreme fluctuating pressure amplitudes and severe gradients that have been observed from experiments.

7-2.1.2 Mid-Field Environments.

7-2.1.2.1 *Mid-Field Vehicle Environment.* In the mid-field areas, the appearance of the exhaust flow as a spatially extended sound source is still of importance in the prediction of acoustic environments. Thus, the extent of the apparent location of the sources then becomes a variable, as well as the apparent source strength.

In predicting the acoustic environment for the vehicle, an analytical/empirical technique is used involving a prediction model based on reference 8. This scheme uses both a dimensionless spectrum function which is proportional to the acoustic power for the dimensionless frequency term known as the Strouhal number (see Figure 7-1) and a source position which is also normalized. The empirical features are based on acoustic data obtained from the skin of various vehicles while the exhaust flows onto a deflector. These data are from a nozzle-deflector height, generally not exceeding the supersonic core length of the flow. The engine operational and geometric parameters (i.e., the nozzle exit diameter) are used to develop the nondimensional and normalized curves. The apparent sound source locations are normalized (Figure 7-2) against the Strouhal number to allow a nondimensional spatial positioning of the source for use in the prediction model. Thus, the sources are located according to frequency down the flow centerline and are denoted to have a given source strength. The vehicle environments are then predicted using the curves and the known vehicle engine parameters. The geometry and strength of the apparent source and the relative location of the vehicle position of interest determine the resulting vehicle acoustic environment.

The equation generally used in the prediction scheme is:

$$\text{OB SPL} = 10 \log_{10}(\text{DSF}) - 10 \log_{10}(2V_e\dot{\omega}/\rho_o C_o D T^2 g N) - 10 \log_{10} R(f) + 10 \log_{10} f_c + 126, \text{ (dB)} \quad \text{(Eq. 7-2)}$$

where:

OB SPL is octave band sound pressure level in dB, Re: 2×10^{-5} newton/m^2

DSF is the dimensionless spectrum function which is a term proportional to acoustic power radiated toward the vehicle for a given Strouhal number, the dimensionless frequency term, fD/V_e.

V_e is the effective nozzle exit velocity (ft/sec)

$\dot{\omega}$ is the weight flow rate (lbs/sec)

ρ_o is the ambient atmospheric density (lb sec^2/ft^4)

C_o is the ambient sound velocity in the atmosphere (ft/sec)

D is the diameter of the nozzle exit (ft)

T is the thrust per engine (lbs)

g is the gravitational constant (ft/sec^2)

N is the number of engines

f is the frequency (Hz)

f_c is the center frequency of the octave band of interest (Hz)

$X_o(f)$ is the apparent source distance (from Figure 7-5) (ft)

X is the distance between the engine nozzle plane and the vehicle position of interest (ft)

$R(f) = X_o(f) + X$ is the distance from the source of a given frequency to the vehicle station (ft).

The curves given with this prediction technique are usable only for deflected supersonic flows (unless other modifications are made for use with undeflected flow cases), i.e., while the vehicle is on-pad for being statically fired. After lift-off, the orientation of the source to the vehicle completely changes. This effect is evident from observing a vehicle acoustic measurement during launch, in time history form. The on-pad vehicle level is reduced by greater than 20 dB after vehicle lift-off, due to the resulting change in relative orientation of the source to the vehicle position. For example, Figure 7-3 shows for Saturn I, SA-4 flight the overall sound pressure level time history (OA SPL in dB, Re: 2×10^{-5} newtons/m^2 versus time in seconds) for a vehicle station 1020 inches above the engine nozzle plane (SA-4 was launched from a wedge deflector). The OA SPL dropped from 152.5 dB to 126 dB, that is,

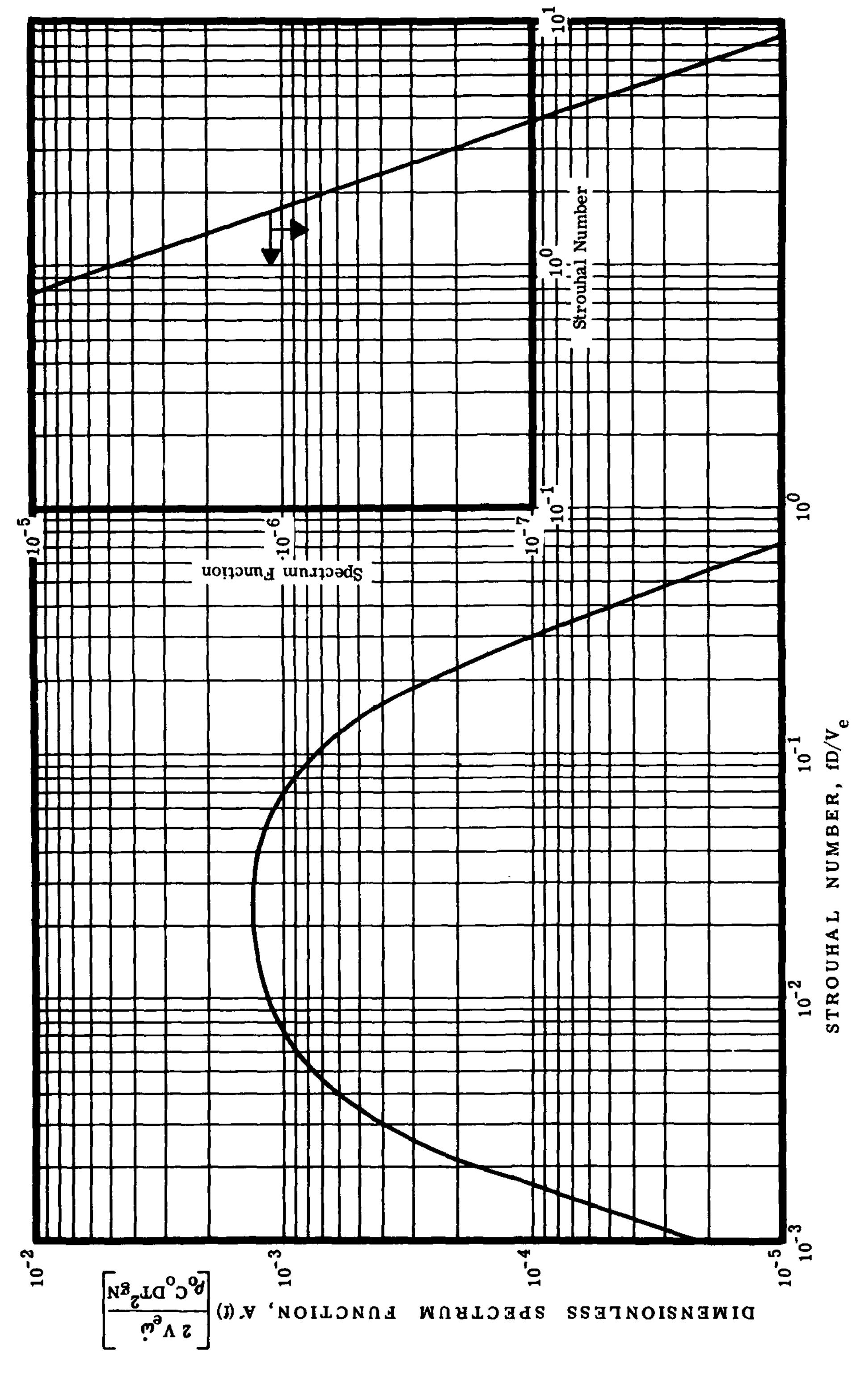


Figure 7-1 Non-Dimensional Spectrum Function versus Strouhal Number

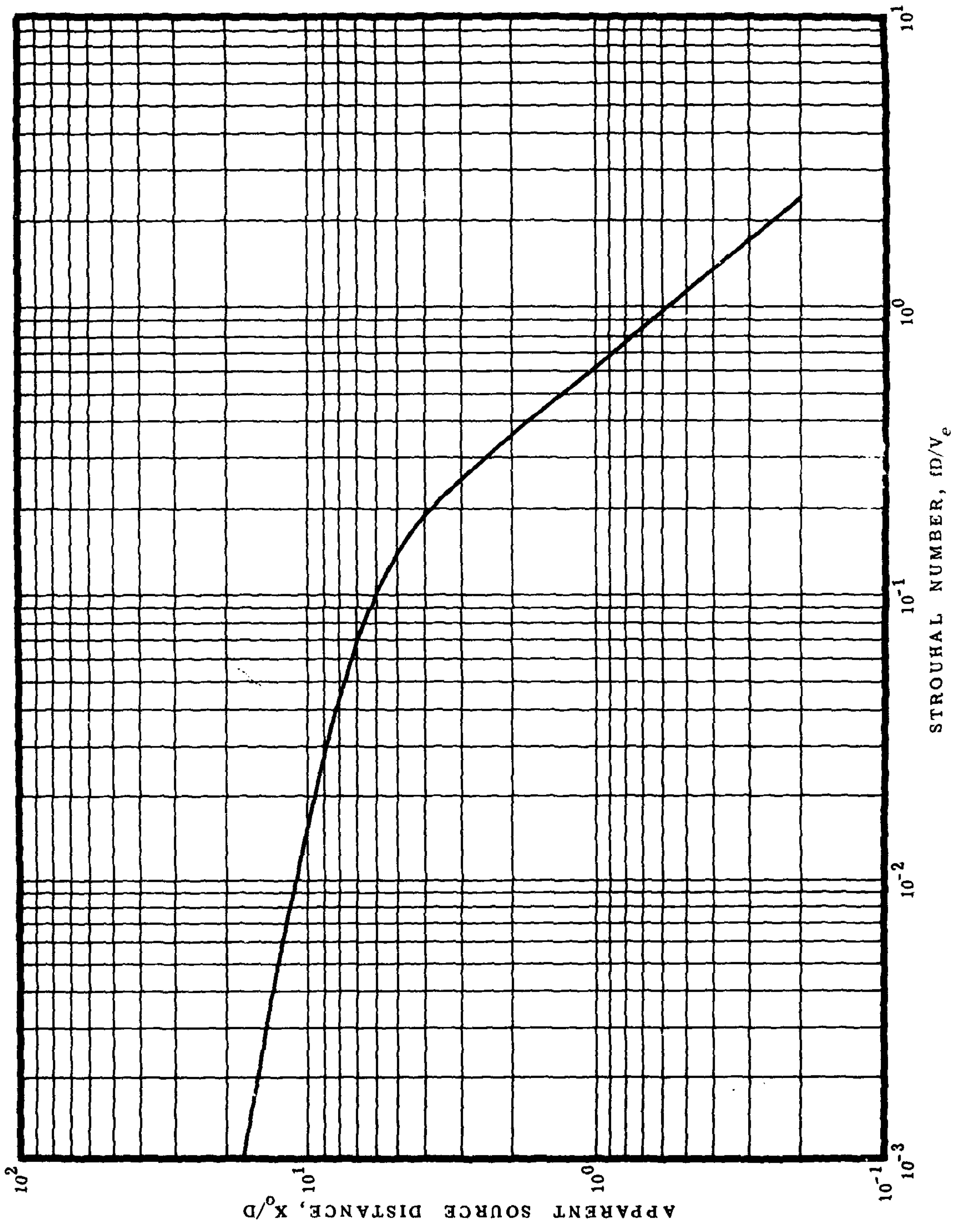


Figure 7-2 Non-Dimensional Apparent Source Distance versus Strouhal Number

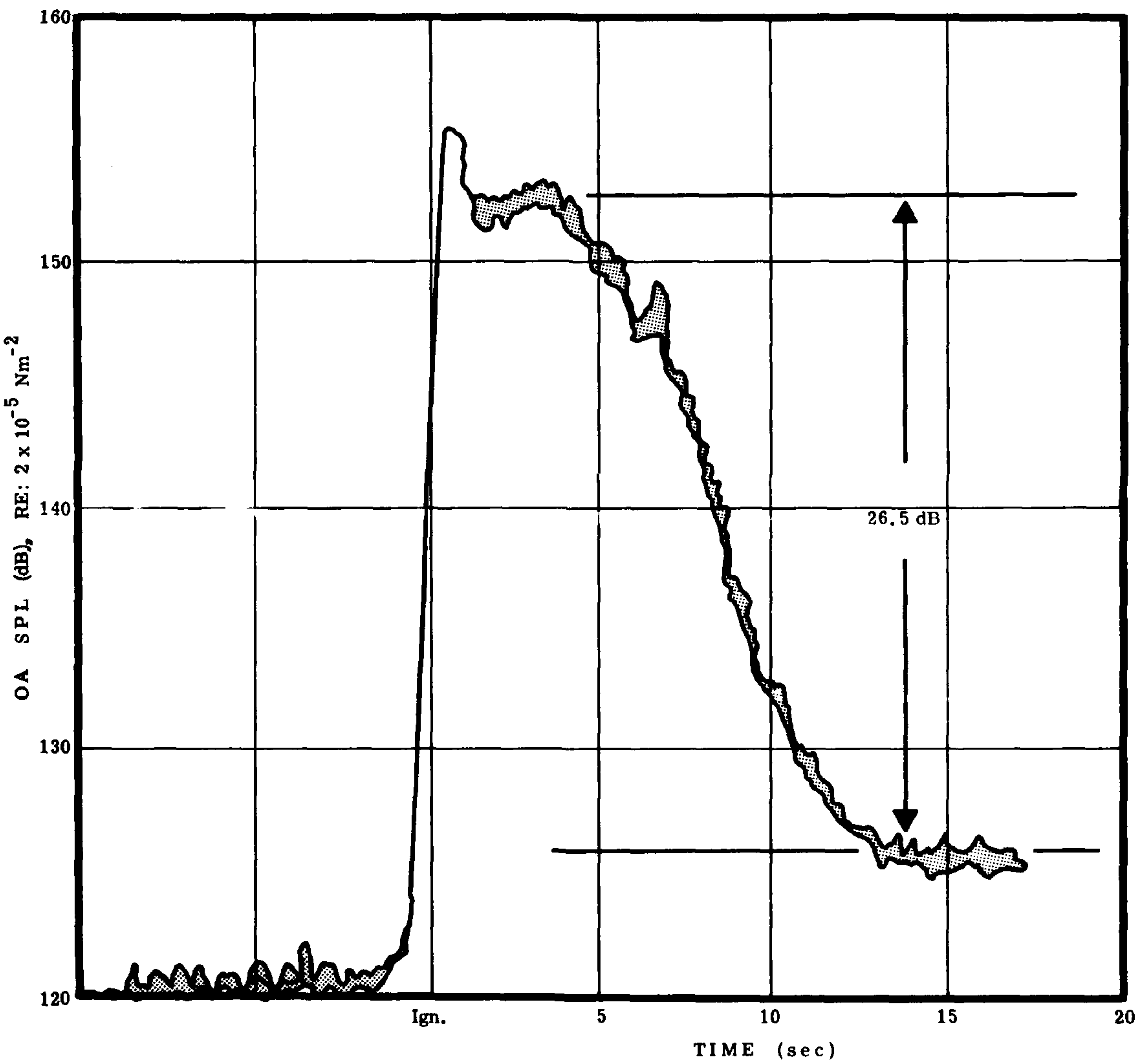


Figure 7-3 Overall Sound Pressure Level Time History Vehicle Station 1020 Inches, Saturn SA-4 Launch

26.5 dB in 9 seconds after lift-off. At this time the flow is no longer influenced by the deflector. In comparison, for most deflectors, the flow is turned from its natural direction as much as 90 to 120 degrees, thereby drastically changing the directivity as viewed from the vehicle position, or in other terms, affecting the power that is radiated back to the vehicle.

In reference 9, the effects on the vehicle environment can be seen for the various flow conditions, i.e., free field undeflected or with the various deflectors. In almost all cases, the data indicate the OA SPL on the vehicle to be lower for undeflected flow than for flow from any of the deflectors, even though the power levels are not significantly higher, and are even sometimes reduced. This decrease in environment is due basically to the directional changes where much of the radiated energy is directed away from the vehicle for undeflected flow; i.e., the vehicle sound pressure level increased appreciably for most deflected conditions. Figures 7-4a and 7-4b compare AS-203 (Saturn IB flight) measured and predicted acoustic spectra for on-pad vehicle acoustic environments at the indicated vehicle stations. Figure 7-4c shows the overall sound pressure level versus vehicle length. These figures support the use of the method described above for estimating the vehicle environment as indicated by the reasonable agreement between predicted and measured values.

7-2.1.2.2 Mid-Field Ground Plane Environment. The environmental conditions of the ground positions in the acoustic mid-field also depend on the spatial distribution of the apparent sources.

Using the previous approach to develop nondimensional curves for predicting the ground plane environment, the apparent spectral distribution of power and apparent source locations change when viewed from different spatial orientations around the vehicle, i.e., for variation in both angle and radius. The source parameters scaled to nondimensional form for the vehicle—they appear the same regardless of viewing from different vehicle locations—cannot be used for general ground plane estimates. However, a similar set of nondimensional curves could be generated for a given radius in the ground plane. Such curves could be used to estimate the environment along that specific radius. The fact that a different set of nondimensional curves is required for each angular orientation creates a large volume of source characteristics (i.e., one set for each radius); thus, computations are practical only on a computer. Because of the large volume of data necessary, it is beyond the scope of this report. Because of the spatial distribution of the sources, the rather significant directivity variations, and in general the three-dimensional properties of the source, the environmental predictions also must be applied to dynamically and geometrically similar conditions.

7-2.1.3 Far-Field Environments.

7-2.1.3.1 Far-Field Ground Plane Acoustic Environment Resulting from Vehicle Launch. The acoustic environments generated during boost phase of the launch of a rocket vehicle naturally increases as the vehicles increase in size; therefore, they are important as a potential structural hazard and as a cause of adverse community reactions. Thus, adequate engineering estimates of these environments are essential. A generalized prediction technique has been developed which is much too involved to discuss at length here. A detailed description of this approach is presented in reference 10. The sound power acoustic source strength characteristics have been generated in the form of a *nondimensional spectrum function which is essentially* in the same form as that described in the section on mid-field environments.

Acoustic efficiency, total acoustic power generation, and the directivity changes have been adjusted for vehicle motion and combined into what is called a "distribution factor." The doppler effects and other such variations observed in the sound source characteristics as viewed from the ground plane are considered, along with divergence and attenuation effects. The description of the sound power characteristics is thus derived from operational parameters of the booster engines and the "distribution factor," which combines the total effects of vehicle velocity, efficiency, directivity changes, etc. This, along with trajectory information, is all that is required as input to define the ground plane acoustic environment for any relative geometry as a function of time. Time-varying octave band spectra, time histories of octave band levels, or overall sound pressure level information at the ground plane observation points can be adequately estimated.

Comparison of predicted with measured data from a variety of vehicles has indicated very good results in most cases, especially in the region of concern where the environments are near maximum values. The measured acoustic environments, for the ground plane, from the Blue Scout, Pershing, Titan, Saturn I and IB, and Saturn V, when compared with the predicted values, were well within the data acquisition accuracy. Noise floor problems prohibit other checks on many other far-field locations (see reference 11). Other improvements are being made to simplify this technique and to reduce the time required to generate the environmental estimates.

Figure 7-5 compares measured octave band spectra for the Titan at a horizontal distance of 5,000 feet, at a 30-second flight time. Figure 7-6 represents the measured overall sound pressure level (OA SPL) time history for the horizontal distance of 24,700 feet from a Saturn I launch compared with several predicted values. Figure 7-7 shows the measured and predicted maximum overall sound pressure levels for the Saturn V launch (AS-501 flight, 1967) versus distance from the launch site. Octave band spectra for a Saturn IB (SA-5) flight are presented in Figure 7-8 at a distance of 16,900 feet to show the applicability of the technique. Figures 7-9 and 7-10 show time histories of the predicted maximum overall sound pressure level for various ground stations for the AS-501 flight along with several measured data points. The results indicate that the technique is relatively accurate for vehicles from the Titan class to the Saturn V. (Reference 12)

7-2.1.3.2 Far-Field Ground Plane Acoustic Environment Resulting from Vehicle Restrained Firing. The general expression which can be used to obtain estimates of the far-field ground plane acoustic environment from a rocket exhaust acoustic source radiating in an inhomogeneous medium (reference 13) can be expressed for

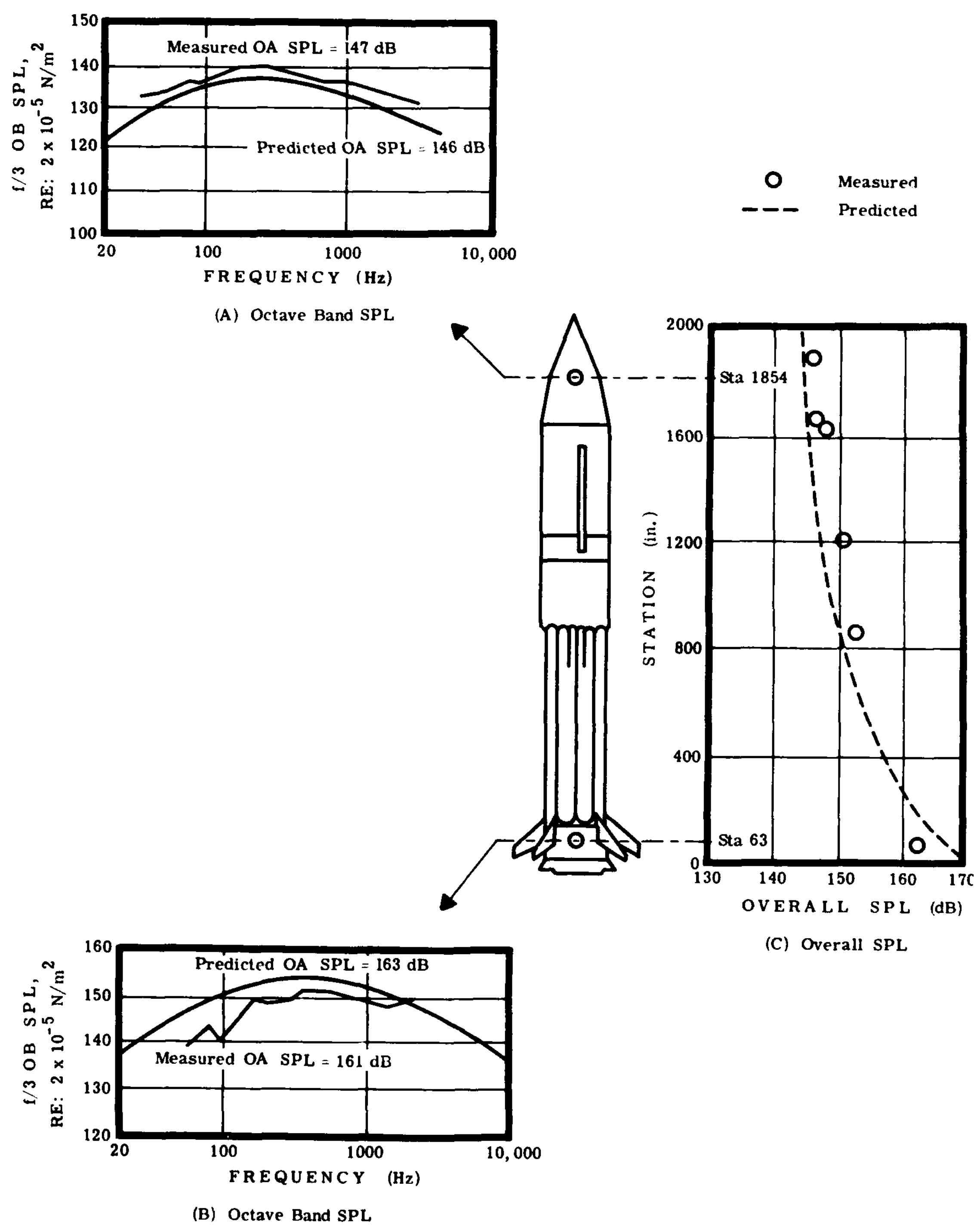


Figure 7-4 On-Pad Acoustic Environments for Apollo-Saturn IB Flight Vehicle AS-203

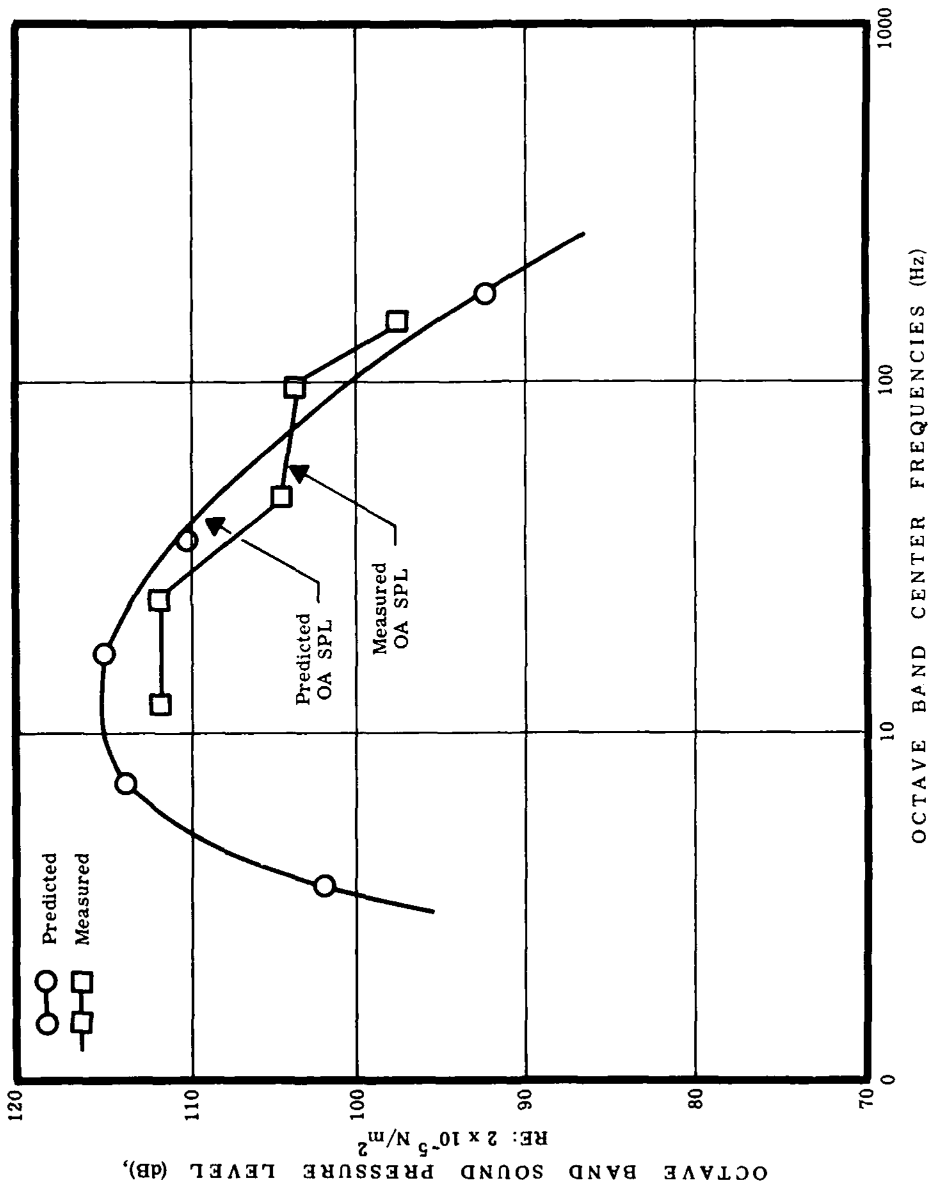


Figure 7-5 Comparison of Measured and Predicted Spectra for the Titan Vehicle at a Horizontal Distance of 5,000 Feet

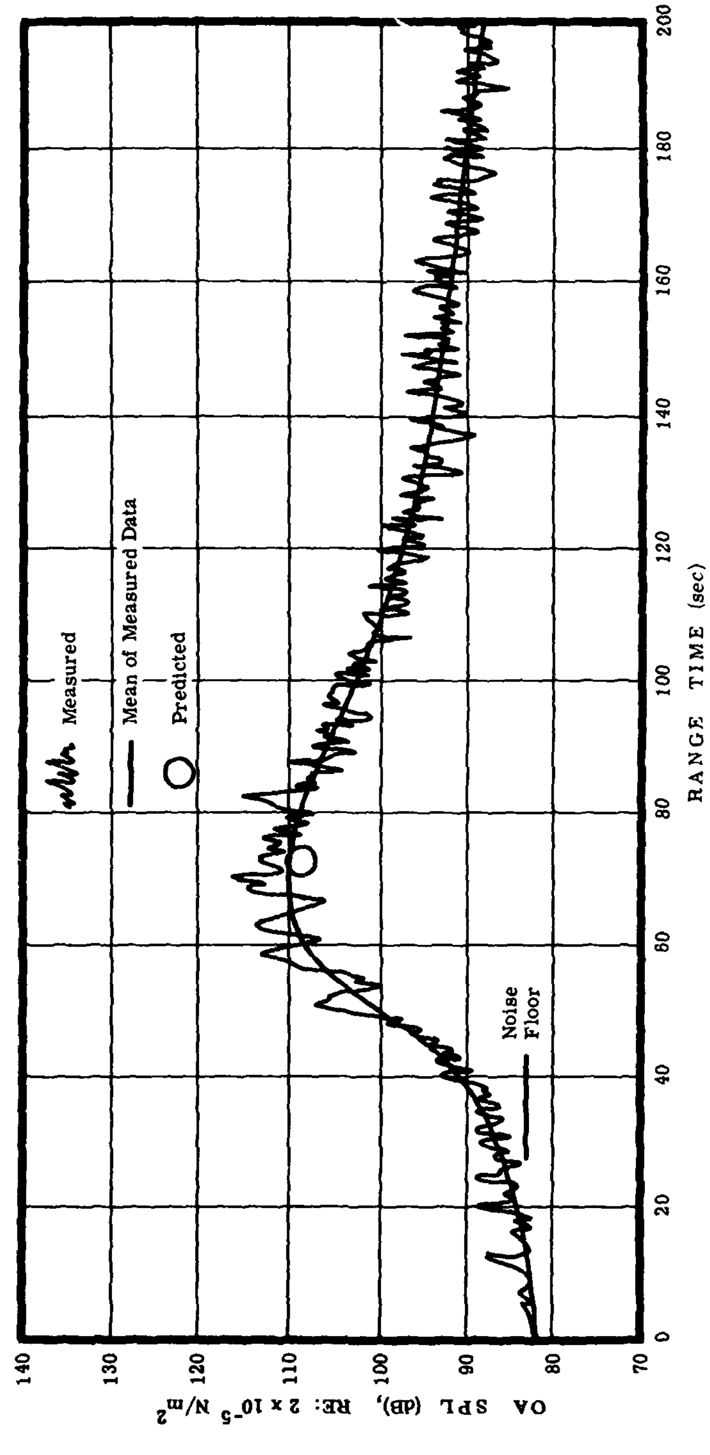


Figure 7-6 SA-3 Overall Sound Pressure Level Time History at a Horizontal Distance of 24,000 Feet

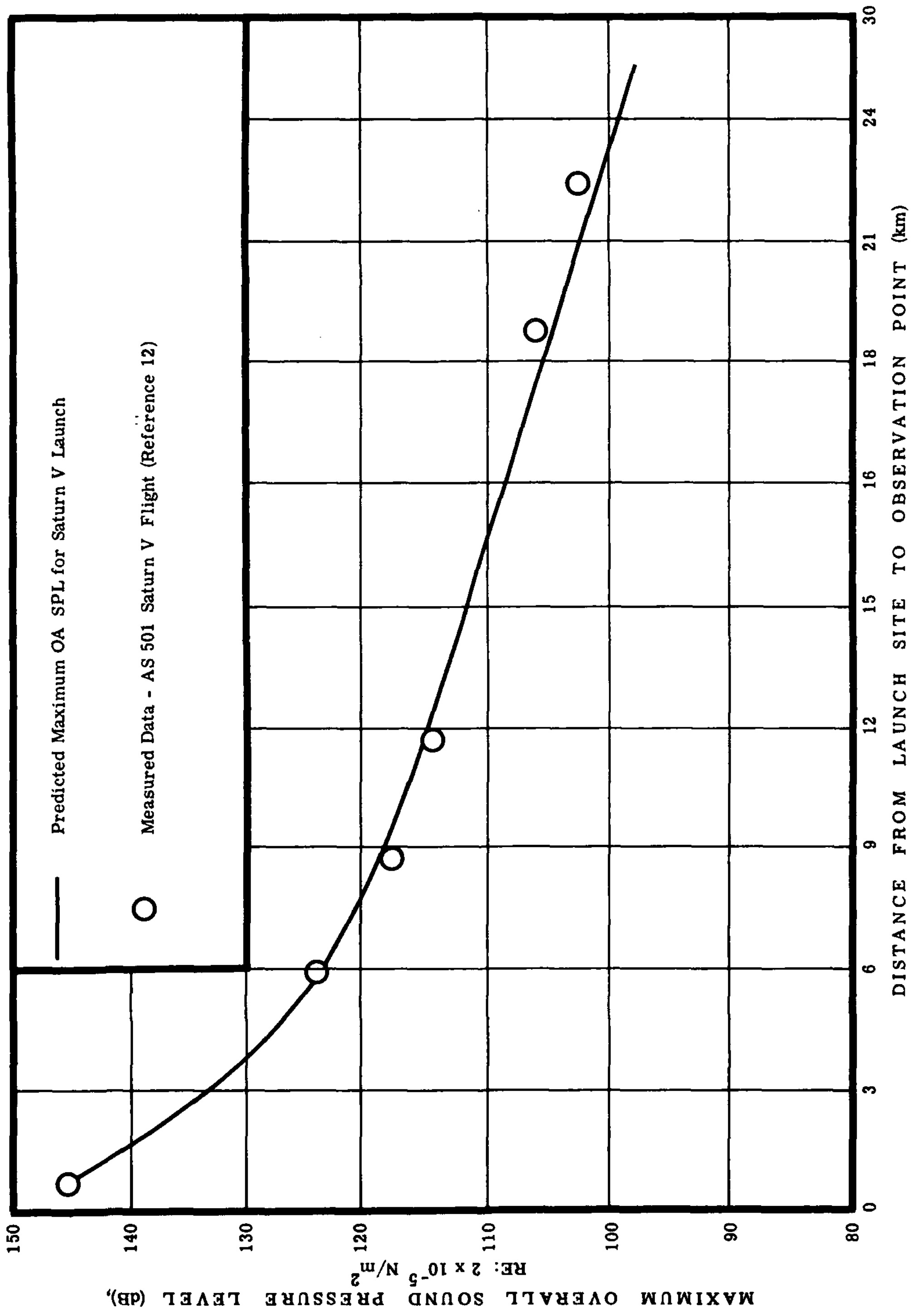


Figure 7-7 Maximum Overall Sound Pressure Level versus Distance from Launch Pad

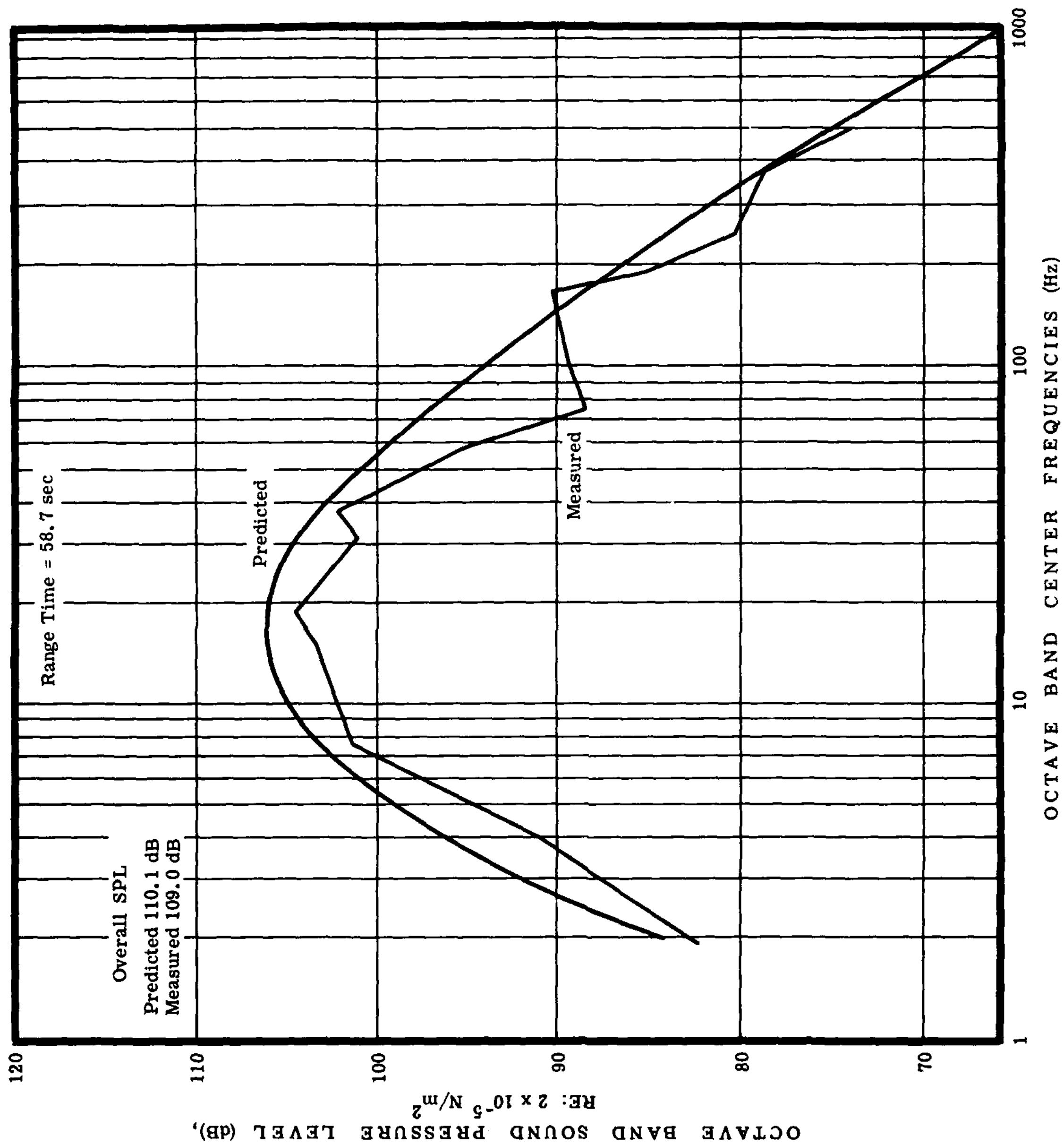


Figure 7-8 Measured Acoustic Data from SA-5 Flight (Saturn I Vehicle) with Predicted Environment at 16,900 ft

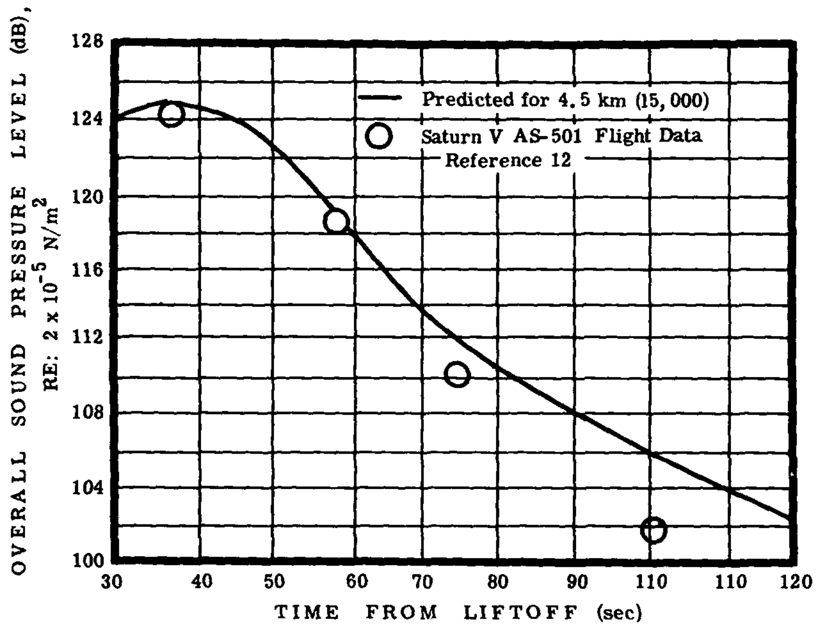


Figure 7-9 Predicted Maximum Overall Sound Pressure Level Time History Saturn V Launch

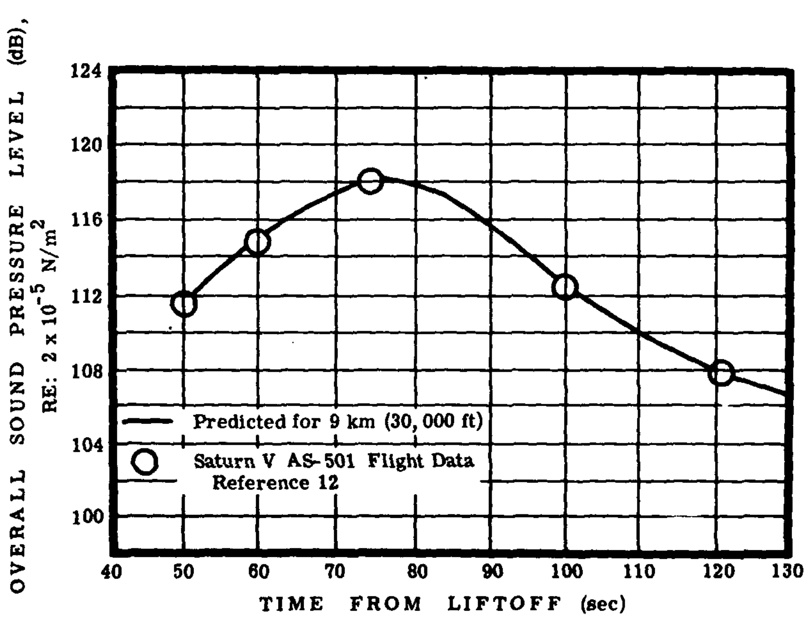


Figure 7-10 Predicted Maximum Overall Sound Pressure Level Time History Saturn V Launch

restrained firing conditions (i.e., static or before lift-off) as

$$SL(f, \alpha, R) = ASL(f) + D.I.(f, \beta) - 20 \log_{10} R - E_A(f, R) + M_F(f, \alpha, R) - 8, \text{ (dB)}$$

(Eq. 7-3)

where:

$SL(f, \alpha, R)$ is the sound pressure spectrum level at the location R along ground plane azimuth angle α measured with respect to the projection of the exhaust centerline on the ground plane; i.e., the mean squared pressure per unit bandwidth, $P^2(f)/Hz$, expressed in decibels (Re: 0.00002 n/m^2Hz), (dB)

$ASL(f)$ is the acoustic power spectrum level from a series of independent, equivalent monopole sources; i.e., the power per unit bandwidth, A(f) expressed in decibels, $10 \log_{10} A(f) 10^{-13}$, Re: 10^{-13} watts/Hz (although Re: 10^{-12} watts is now widely accepted, the stated reference is used in this report for convenience), (dB)

$D.I.(f, \beta)$ is the directivity index; describes the radiation characteristics of the source, (deviation from the symmetrical radiation of the equivalent monopole source) where β is the angular orientation of the receiver with respect to the centerline of the exhaust flow, (dB)

R is the distance from source to receiver (ft)

$E_A(f, R)$ is the excess attenuation; the attenuation due to molecular absorption of the sound energy by the atmosphere, (dB)

$M_F(f, \alpha, R)$ is the meteorological factor. This describes the effect of the inhomogeneities of the atmosphere on the sound energy. Positive values indicate an increase of the sound energy above the case of homogeneous conditions; negative values indicate shadow zones, and a value of zero indicates a homogeneous atmosphere, (dB).

Equation 7-3, given in sound pressure spectrum level form, can be converted to any given band level form as follows:

$$SL(f_c, \alpha, R) + 10 \log_{10}(\Delta f) = SPL_{\Delta f}(f_c, \alpha, R)$$

(Eq. 7-4)

where Δf is equal to the bandwidth of interest in Hertz and $SPL_{\Delta f}(f_c, \alpha, R)$ is the sound pressure level in the band Δf at the band's center frequency, f_c. The above expression is valid as long as the mean squared pressure does not change greatly within the band. For the normal case of octave or one-third octave sound pressure levels Δf becomes 0.707 f_c and 0.231 f_c, respectively. The octave band expression is, therefore,

$$OB\ SPL = SL(f_c, \alpha, R) + 10 \log_{10}(0.707 f_c), \text{ (dB)}.$$

(Eq. 7-5)

It is seen from the above expression that, to obtain predictions of the far-field acoustic environment, the equivalent monopole acoustic source and directivity characteristics, as well as the effects of the propagation medium on the sound energy, must be considered. The latter effects (attenuation and refraction) are discussed more fully in another section. For the purpose of the discussion which follows, it will be assumed that the atmospheric medium is homogeneous; i.e., $M_F(f, \alpha, R) = 0$.

The spectral distribution of acoustic power A(f) is normally obtained from far-field sound pressure measurements by first converting the pressure measurements for each frequency, or frequency band of interest, to the acoustic power radiated through a given slice of a hemispherical area (assuming symmetrical radiation characteristics about the centerline of the exhaust flow) and then summing the power from each slice over the total hemisphere. The resulting power distribution is then assumed to represent the strength of equivalent monopole sources for the various frequencies.

The sum of the power over the total frequency range is, then, the total acoustic power which is defined as

$$A_{OA} = \int_0^\infty A(f)\, df$$

(Eq. 7-6)

where:

A_{OA} is the total acoustic power, and is used to collapse and normalize the acoustic power characteristics from a wide variety of data, (watts)

A(f) is the spectral distribution of the equivalent monopole acoustic power, i.e., the power radiated per unit bandwidth, (watts/Hz).

The normalized acoustic power characteristics from a variety of rocket exhaust flows is presented in Figure 7-11 (see Potter and Crocker in Reference 14 for other normalizing forms). This figure represents the normalized source strength of equivalent monopole sources at the desired frequencies. The acoustic data used to arrive at the normalized power curve were obtained from the exhaust flow configurations in Table 7-1. The engine parameters associated with these configurations are shown in Table 7-2.

Figure 7-11 shows that the data collapses reasonably well using the concept of an "effective diameter." Effective diameter is defined as the square root of the number of engines of a given engine cluster times the diameter of a single engine ($(D_e = (N)^{\frac{1}{2}} D_s)$), or a single engine with a diameter that would have the same flow density and mass flow as the total cluster. Even though these data were obtained from both deflected and unde-

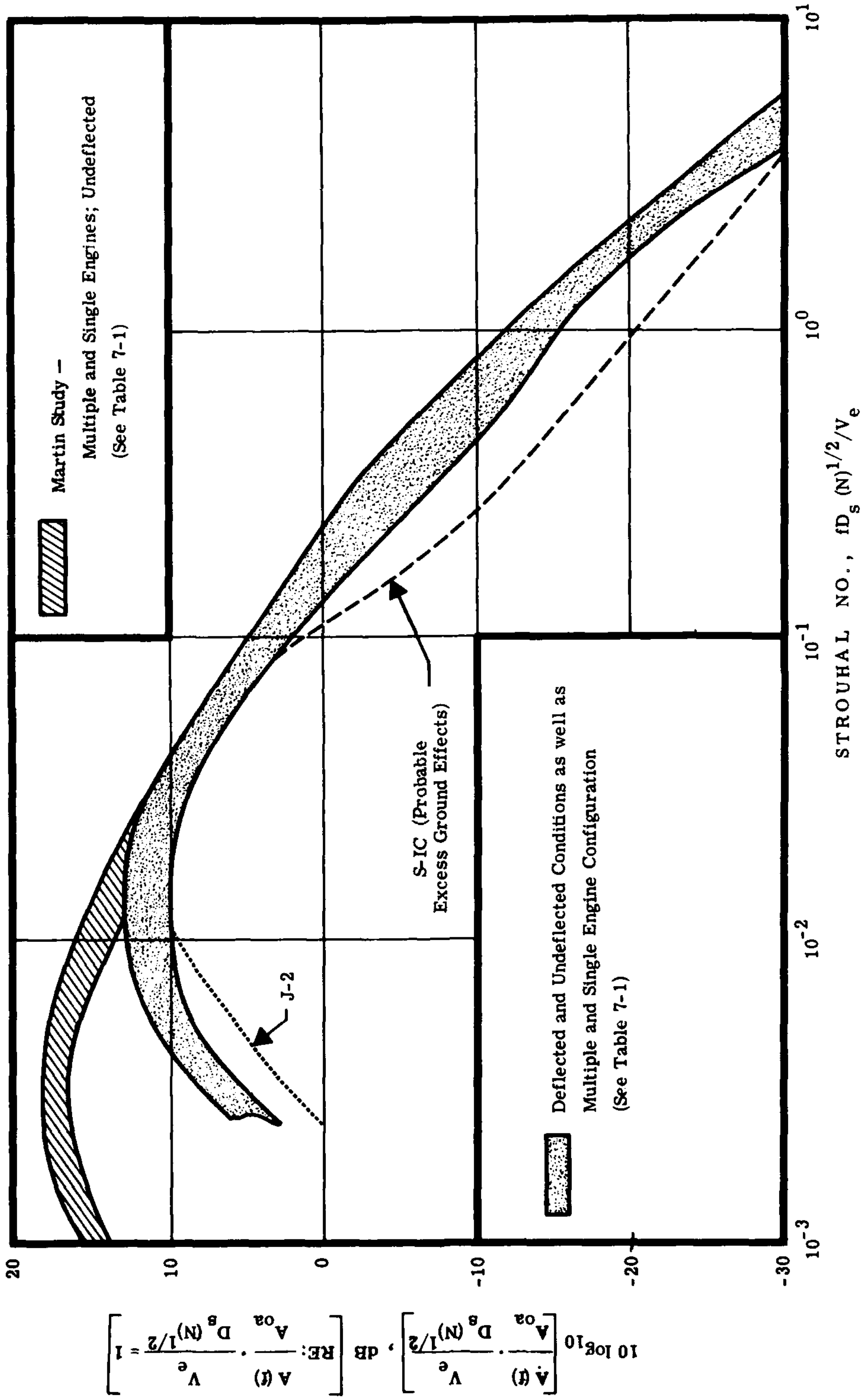


Figure 7-11 Dimensionless Acoustic Power Spectrum Level for Deflected and Undeflected Exhaust Flows

Table 7-1
Engine and Stage Test Information

Type Propulsion System	Type Propellant	No./Type of Engines	Deflector Configuration	Mech. Power (watts)	OA PWL (Re: 10^{-13}w) (dB)	Acoustic Power (watts)	Acoustic Efficiency η(%)
J-2	LO_2/LH_2	1/J-2	90° bucket	9.8×10^8	193.5	2.24×10^6	.229
S-II	LO_2/LH_2	5/J-2	90° bucket	4.9×10^9	197.1	5.13×10^6	.105
F-1	LO_2/RP-1	1/F-1	120° bucket	9.5×10^9	204.5	2.82×10^7	.297
S-IC	LO_2/RP-1	5/F-1	105° bucket	4.75×10^{10}	212.5	1.78×10^8	.375
S-1, Bk I	LO_2/RP-1	8/H-1	120° bucket	7.35×10^9	203.3	2.14×10^7	.297
S-1, Bk II	LO_2/RP-1	8/H-1	120° bucket	8.6×10^9	204.2	2.63×10^7	.306
1/20 Scale F-1	LO_2/RP-1	1/Scale F-1	None	2.38×10^7	180.6	1.15×10^5	.487
Martin Jet (ref. 14)	O_2/H_2	$1/O_2H_2$	None	3.5×10^7	171.3	1.35×10^4	.386
Martin Jet	O_2/H_2	$5/O_2/H_2$	None	1.75×10^7	177.5	5.8×10^4	.331
Martin Jet	O_2/H_2	$8/O_2/H_2$	None	2.80×10^7	178.3	6.6×10^4	.236
Martin Jet	O_2/H_2	$12/O_2/H_2$	None	4.2×10^7	179.2	8.75×10^4	.208
KIWI B (ref. 15)	Nuclear	H_2	None	4.65×10^8	190.8	1.2×10^6	.258
JATO (ref. 9)	Solid	1/Solid	None	5.3×10^6	170.2	1.05×10^4	.198

Table 7-2
Engine Parameters

Type Engine	Thrust (lbs)	Flow Rate (lbs/sec)	Exit Velocity (ft/sec)	Expansion Ratio	Exit Diameter (in)	Specific Impulse (sec)	Exit Mach No.	Chamber Pressure (lbs/in^2)
J-2 (sea level)	150,000	500	9,650	27.5/1	77.2	300	3.2	670
F-1	1,500,000	5690	9,320	16/1	139.5	264	3.7	1090
H-1, Bk I	165,000	670	8,200	8/1	45.7	250	3.2	650
H-1, Bk II	188,000	735	8,420	8/1	45.7	256	3.2	650
1/20 Scale F-1	4,000	14.7	8,780	16/1	6.84	272	3.7	1020
Martin Jet (ref. 14)	400	1.0	12,900	10/1	1.56	400	3.5	1200
KIWI B (ref. 15)	38,300	69	17,900	-	30.0	555	3.7	-
JATO (ref. 9)	1,020	4.32	7,600	6.76/1	2.6	236	2.9	900

flected exhaust flows, they still scale according to an effective diameter. It is well known that the presence of the deflector considerably alters the sound radiation characteristic of the exhaust flow for a given spatial location. This is easily verified by the increased levels at the vehicle position (Figure 7-6) when in the deflected condition (reference 9).

Cole, et al (reference 9) conducted a series of tests which generally indicated that the peak frequency in the equivalent monopole acoustic power spectrum shifted progressively to lower frequencies when going from a flat-plate type of deflector, to a bucket-type of deflector, to the free-field condition. Even though the present data indicate that the characteristic length dimension for scaling is the effective diameter, this could actually be masking another characteristic scaling length based upon some deflector dimension such as width. This cannot be resolved at this time, but in any event, the scaling parameters indicated in Figure 7-11 will provide reliable engineering estimates with respect to the large boosters of current space vehicles and those of the immediate future. For the case of scaling only free-field exhaust flows, the low Strouhal range of Figure 7-11 shows that the effective diameter does well in collapsing the data from circular cluster configurations of 1, 5, 8, and 12 engines (reference 16). These data, however, do not collapse very well in the same Strouhal range with the rest of the data. The shift seems to be a factor of four lower in frequency for the circular cluster data. These data were obtained from engines which used gaseous hydrogen and gaseous oxygen propellants; however, the majority of the data presented in Figure 11 were obtained from rocket engines using LO_2/LH_2 and LO_2/RP-1 propellant (cryogenics). This frequency shift in the normalized power spectrum indicates the need for maintaining flow similarity. For example, if predictions are to be made for a rocket exhaust system that uses LO_2/RP-1, then normalized data from a LO_2/RP-1 system should be used and not data from, for example, a cold exhaust flow.

Another very important far-field acoustic source parameter is the acoustic efficiency of a given propulsion system defined as:

$$\eta = A_{OA}/M_P = A_{OA}/0.678\ TV_e \quad \text{(Eq. 7-7)}$$

where:

η is the acoustic efficiency

A_{OA} is the total acoustic power (watts)

M_P is the total jet stream mechanical power (watts)

T is the total thrust (lbs)

V_e is the effective exhaust exit velocity for a single engine (ft/sec).

Figure 7-12 indicates the total acoustic power as a function of jet stream mechanical power with acoustic efficiency as a parameter. The acoustic efficiency for current types of exhaust flow conditions generally lies within the range of 0.1 to 0.5 percent. This is indicated by the measured data points presented on the figure. The acoustic efficiency range is expected to be the same for larger, more advanced space vehicle systems of conventional engine design.

The efficiency factor allows the estimation of the overall acoustic power that a rocket propulsion system generates, and when used with the normalized power curves, yields the strength of an equivalent monopole source for any given frequency. The monopole source has symmetrical radiation characteristics; however, the actual exhaust system radiates energy in a highly directional manner. To account for this directivity or deviation from symmetrical radiation, experimental data can be used to obtain curves which indicate the directivity for a given frequency as a function of the angular orientation about the centerline of the exhaust flow. These values are called the "directivity indices."

Typical directivity indices for deflected flows were derived from a series of repeatable F-1 (1.5×10^6 lb thrust) LO_2/RP-1 engine acoustic data and are presented for octave frequencies. The directivity indices presented in Figures 7-13(a) through 7-13(e) agree well with those derived from experimental data from other large booster systems (Redstone, Saturn I, H-1 engine, Saturn 1B, Saturn V, etc.). The directivity curves for the deflected flow conditions are applicable to current large space vehicle boosters and those of the immediate future, as long as these propulsion systems create similar flow fields.

Directivity indices for a scaled model of the F-1 engine fired in an undeflected configuration were frequency scaled to prototype conditions by using Strouhal scaling parameters. These scaled directivity values were compared to the directivity values of the deflected flow F-1 engine to examine the effects of the deflector on the direction radiation characteristics. The results for given octave band center frequencies are also presented in Figures 7-13(a) through 7-13(e). This comparison, in general, indicates that deflecting the flow seems to shift the direction of maximum radiation to lower angles, i.e., closer to the exhaust centerline. Additionally. Atvars, et al., (reference 17) show that the angle of maximum radiation increased with increasing exit velocity.

The preceding generalized description of acoustic source characteristics, such as the normalized spectral distribution of equivalent monopole acoustic power, acoustic efficiency and directivity indices, allows estimation of the sound pressure at any far-field location for current and future large space boosters with similar propulsion systems. The general procedure is as follows:

a. First, determine the basic operational characteristics of the rocket engine propulsion system, i.e., flow rate, exit velocity, mechanical power, etc.

b. Determine the total acoustic power by using Equation 7-6 and assuming an acoustic efficiency value $0.1 \leq \eta \leq 0.5$ percent. A conservative approach would be to let $\eta = 0.5$ percent.

c. Depending upon flow conditions, determine the appropriate nondimensional acoustic power characteristics

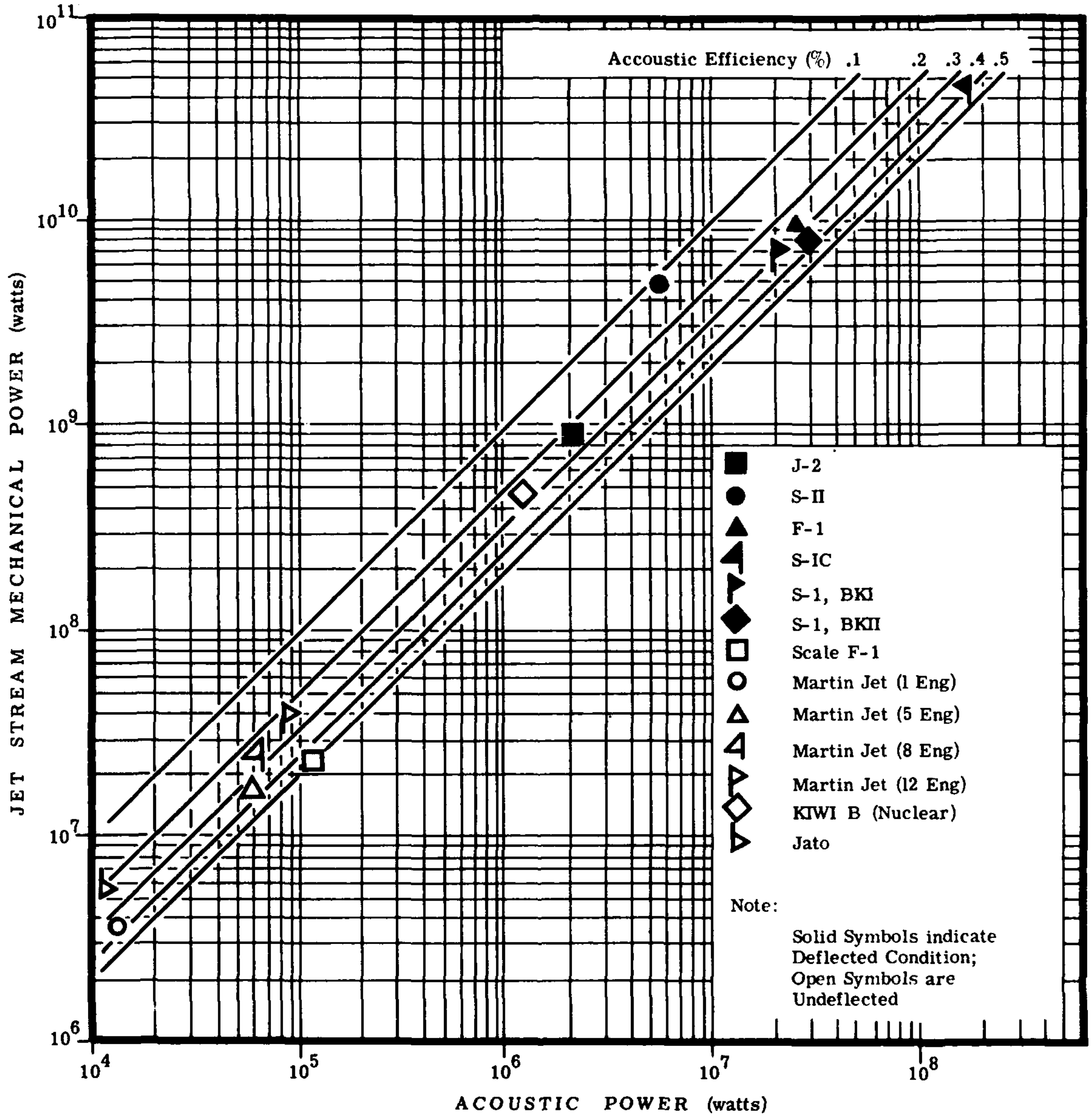


Figure 7-12 Acoustic Efficiency Trends

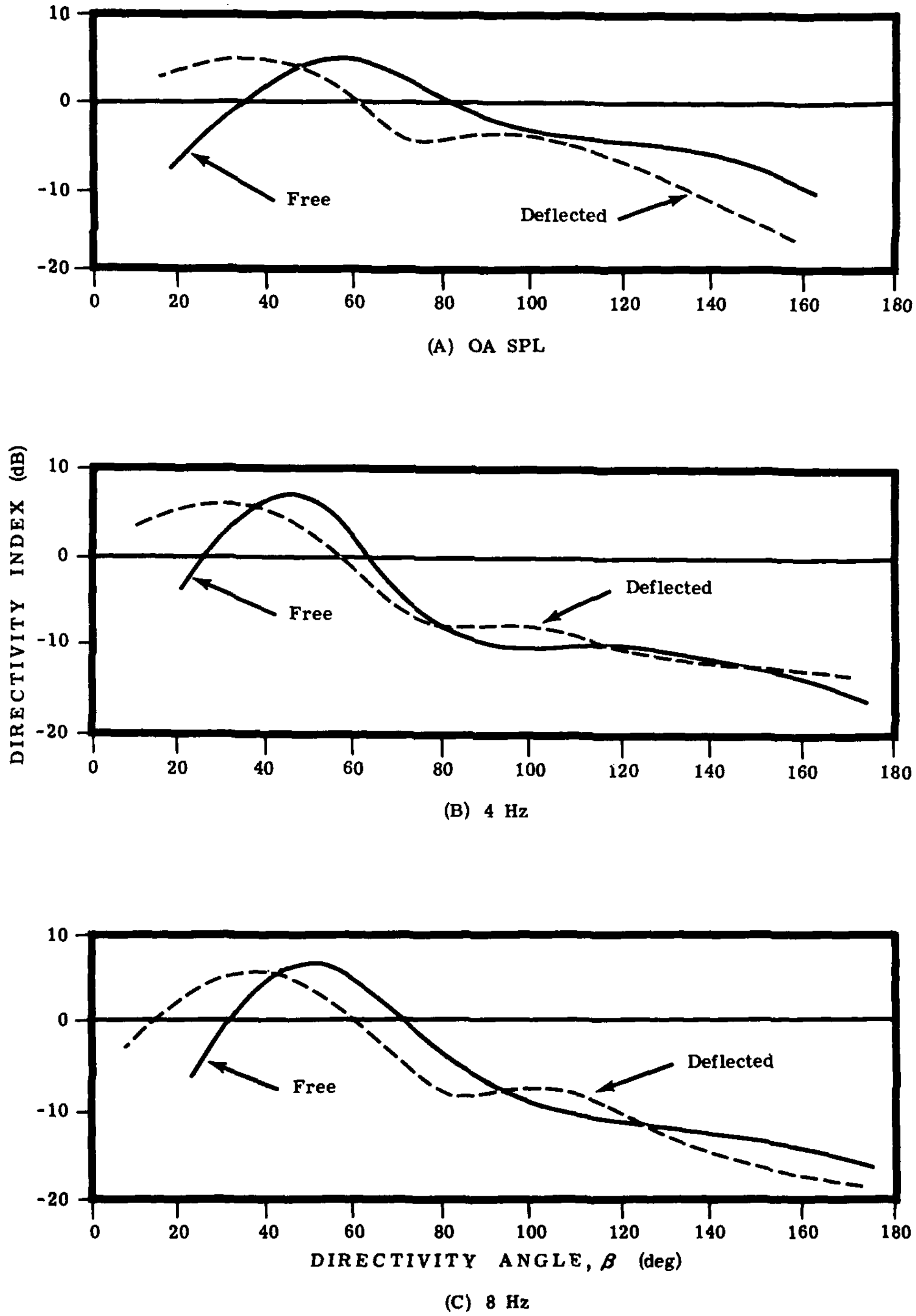


Figure 7-13 Typical Directivity Indices for Deflected and Free Field Condition (Measured from the centerline of the deflected exhaust)

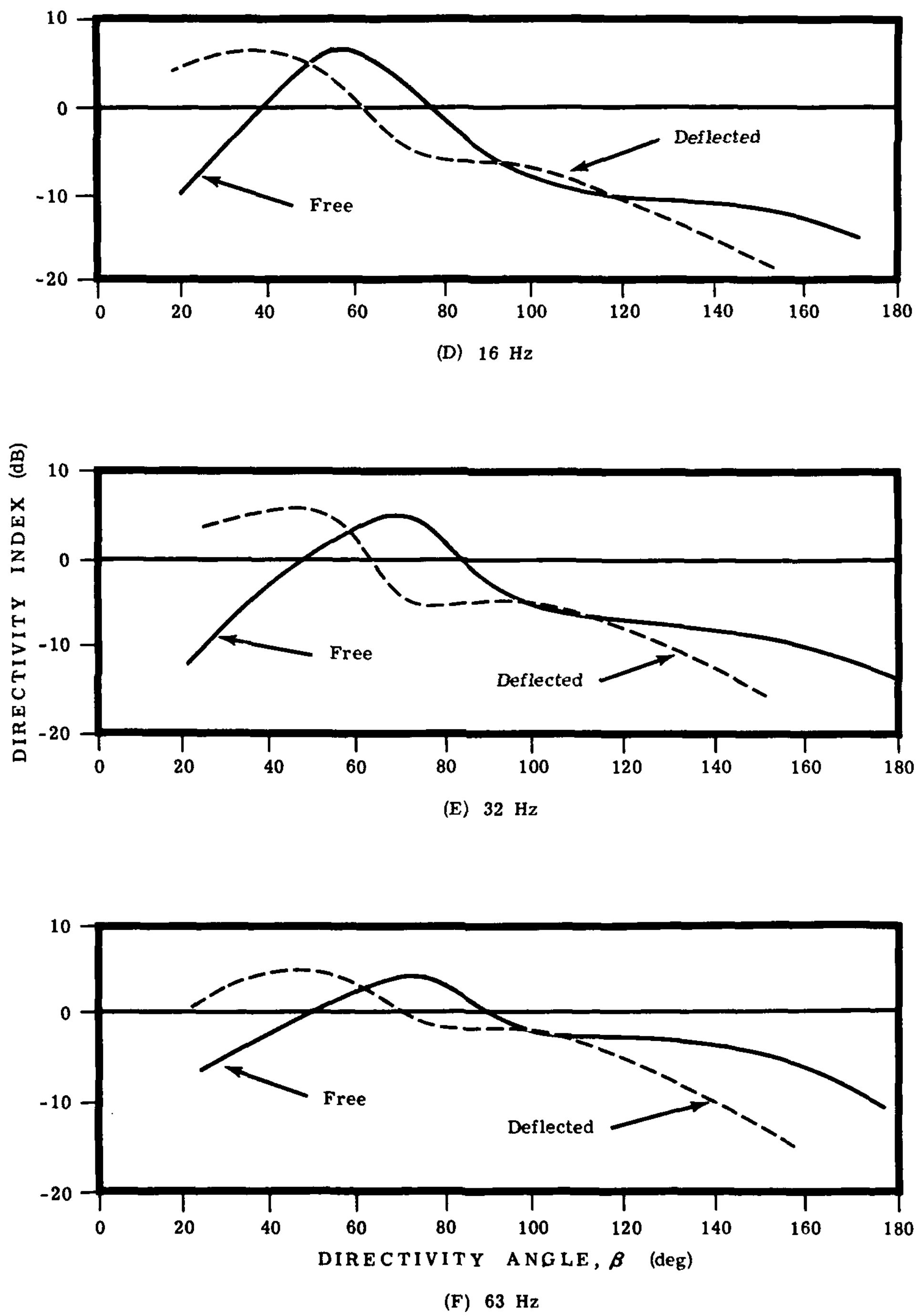


Figure 7-13 Typical Directivity Indices for Deflected and Free Field Condition (Cont'd)
(Measured from the centerline of the deflected exhaust)

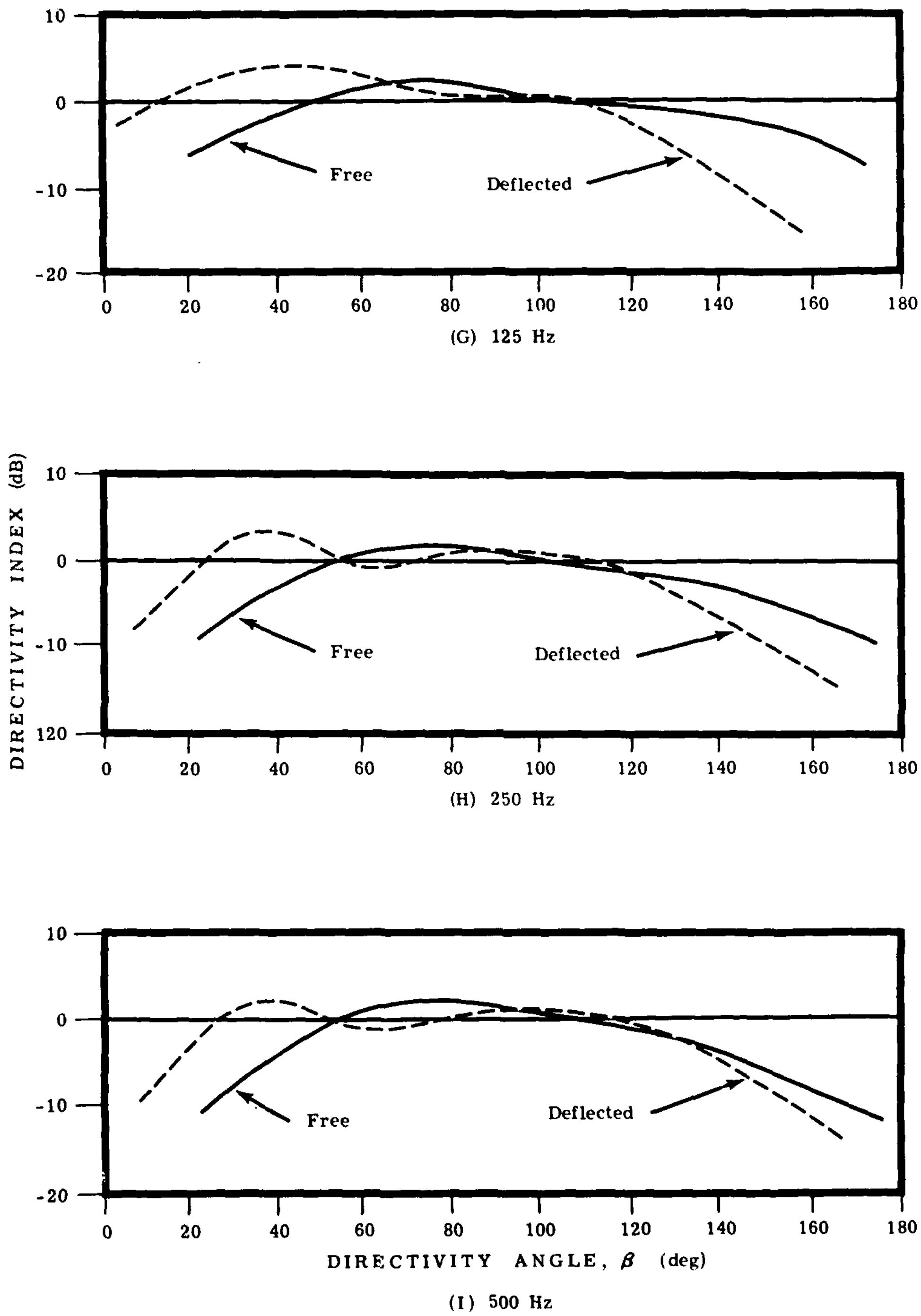
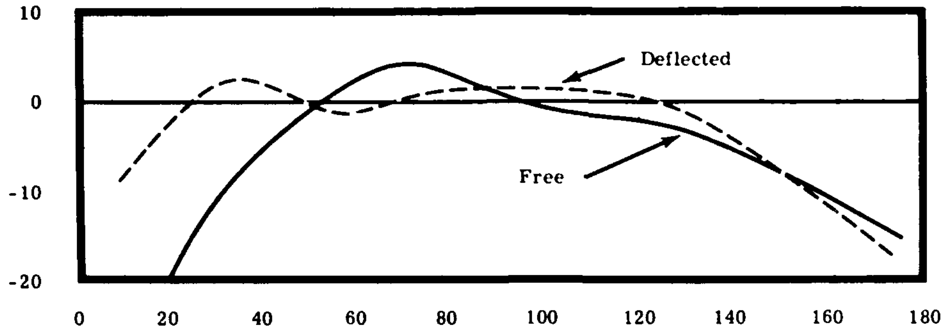
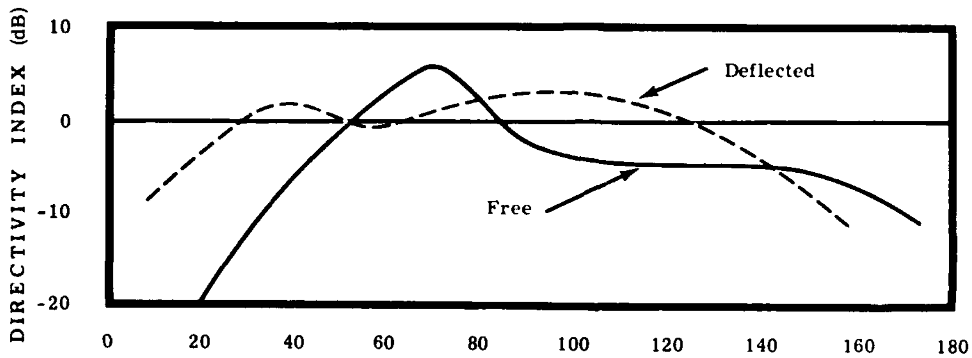


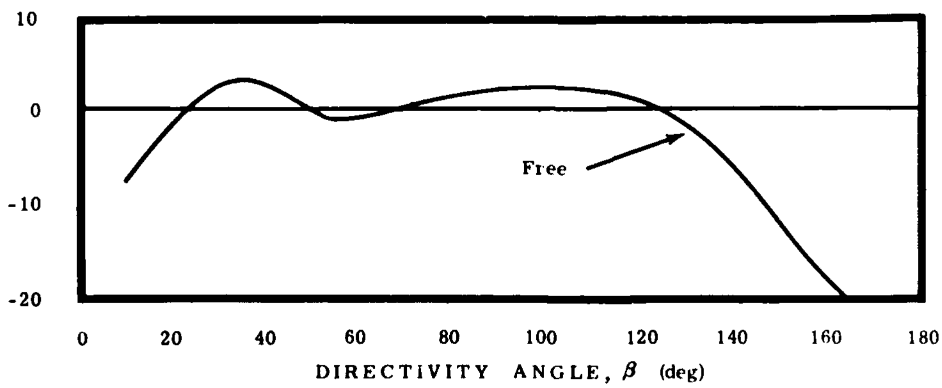
Figure 7-13 Typical Directivity Indices for Deflected and Free Field Condition (Cont'd) (Measured from the centerline of the deflected exhaust)



(J) 1000 Hz



(K) 2000 Hz



(L) 4000 Hz

Figure 7-13 Typical Directivity Indices for Deflected and Free Field Condition (Cont'd) (Measured from the centerline of the deflected exhaust)

from Figure 7-11 and then calculate the acoustic power spectrum level for the proposed system.

d. Select the appropriate directional characteristics, deflected or undeflected, from Figures 7-13(a) through 7-13(l), depending upon the vehicles' operational configuration.

e. Evaluate the atmospheric effects. For a first approximation assume the ideal conditions of a homogeneous standard atmosphere (i.e., $M_F(f, \alpha, R) = 0$). The loss of sound energy by molecular absorption can be estimated by use of Figure 7-14. (Also see Section on atmospheric effects and Figure 7-15.) Refractive properties of actual prevailing atmospheric conditions should be seriously considered. In some cases, the meteorological factor term of Equation 7-3, $M_F(f, \alpha, R)$, can be as large as 20 dB or more (see the discussion on atmospheric effects, Section 7-2.2.

f. After evaluation of all the above factors, Equation 7-3 can be used to determine the sound pressure spectrum level at any far-field ground plane location. The general expression in Equation 7-4 can be used to convert the spectrum levels to band level form. The expression used to convert to octave band sound pressure levels (OB SPL) is presented in Equation 7-5. These are the conventional modes of spectral presentation for environmental estimates.

g. The overall sound pressure level (OA SPL) can then be determined in the usual manner by combining the mean squared pressure from all bands; i.e.,

$$\overline{P^2_{OA}} = \sum_{i=1}^{N} P^2_{\Delta f_c}\,(f_{ci}) \qquad \text{(Eq. 7-8)}$$

where $\overline{P^2_{OA}}$ is the overall mean squared pressure and $P^2_{\Delta f}(f_{ci})$ is the mean squared pressure in the frequency band centered at f_{ci}.

$$\text{OA SPL} = 20 \log_{10} \frac{\sqrt{\overline{P^2_{OA}}}}{0.0002\ \text{N/m}^2}, \text{(dB)}. \qquad \text{(Eq. 7-9)}$$

Although this procedure may seem rather cumbersome, it is fairly straightforward.

h. If the flow field is split into two or more parts, for example, by a wedge deflector, each flow stream should be treated independently with respect to the directional radiation properties and acoustic environmental estimates for each stream made. The resultant environments should then be combined with one another in the conventional manner. This approach should also be used when strap-ons further complicate the problem. Each far-field environment (for each stream) can be estimated independently and the results combined. For these more complicated situations, more complicated radiation patterns will result.

The far-field overall sound pressure level has been computed, using the above procedure, for the static firing of the S-IC stage of the Saturn V vehicle. The results are presented in Figure 7-14 for homogeneous atmospheric conditions. This figure shows predicted contours of equal overall sound pressure level values. Although measured data are not presented on the figure, it compares very well with the estimated results.

7-2.2 EFFECTS OF THE PROPAGATIONAL MEDIUM.

7-2.2.1 Atmospheric Effects. The atmosphere through which the rocket noise propagates can have a pronounced effect on the characteristics of the sound observed at a point in the far-field. The sound, leaving the source, is absorbed, refracted, and dispersed by the atmospheric medium controlled by prevailing meteorological conditions.

The classical absorption effects resulting from viscous and thermal losses are usually negligible in the low frequency range of sound generated by large boosters. Molecular absorption of the rocket noise is believed to be the predominant cause of excess attenuation (i.e., over and above divergence and classical absorption). Many conflicting results (References 18 to 26) have been reported from various studies of the excess attenuation phenomenon from both laboratory and field data. No generally accepted values for the attenuation exist for the frequency range of interest for large space vehicles. Figure 7-15 indicates the spread that is found from the laboratory and field results. No reasons for the widely different results are readily discernible.

In Figure 7-16 the excess attenuation values represent those values which appear to be compatible with respect to far-field acoustic data from current rocket tests. This information, obtained from references 19, 20, 21 and 26, is roughly an average of the field data that appear to comply with observations. The conditions which generally prevailed for the acquisition of the data used to obtain Figure 7-16 included relative humidity values from 50 to 80 percent and temperatures from 40 to 70°F. This curve (Figure 7-16) is thus applicable when conditions correspond to those cited; however, when extreme atmospheric variations are encountered, such as very low relative humidity or temperatures, caution should be used. The appropriate data from the literature where the relative influences of temperature, humidity, and atmospheric pressure have been studied, should be consulted and applied to the problem.

Comparison of predicted with measured environments indicates that Figure 7-16 provides excess attenuation values which are well within the spread of the total accuracy of the prediction techniques.

There are other factors influential to the acoustic energy propagation which tend to mask any one effect, such as excess attenuation. The problem of data spread or variability due to refraction, ground cover absorption, etc., prevents a unique determination of the accuracy related specifically to the molecular absorption and to the accuracy of data presented in Figure 7-16. When involved with other studies, the excess attenuation phenomenon thus presents itself likewise as an undesirable, and somewhat prevents the accurate and unique determination of other influences on the data, such as the refraction of the sound wave, etc.

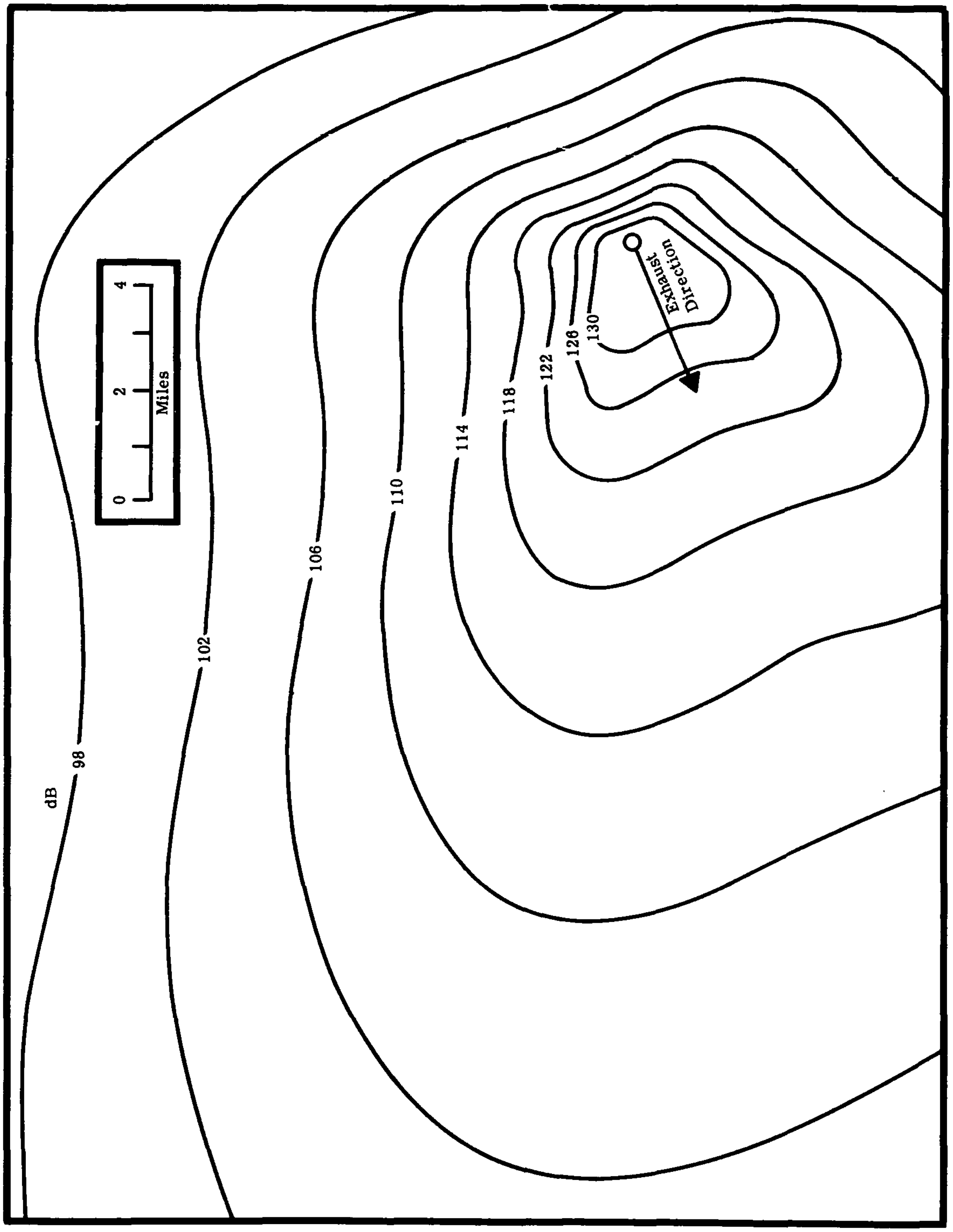


Figure 7-14 Constant Overall Sound Pressure Level Contours in dB Resulting from an S-IC Static Firing

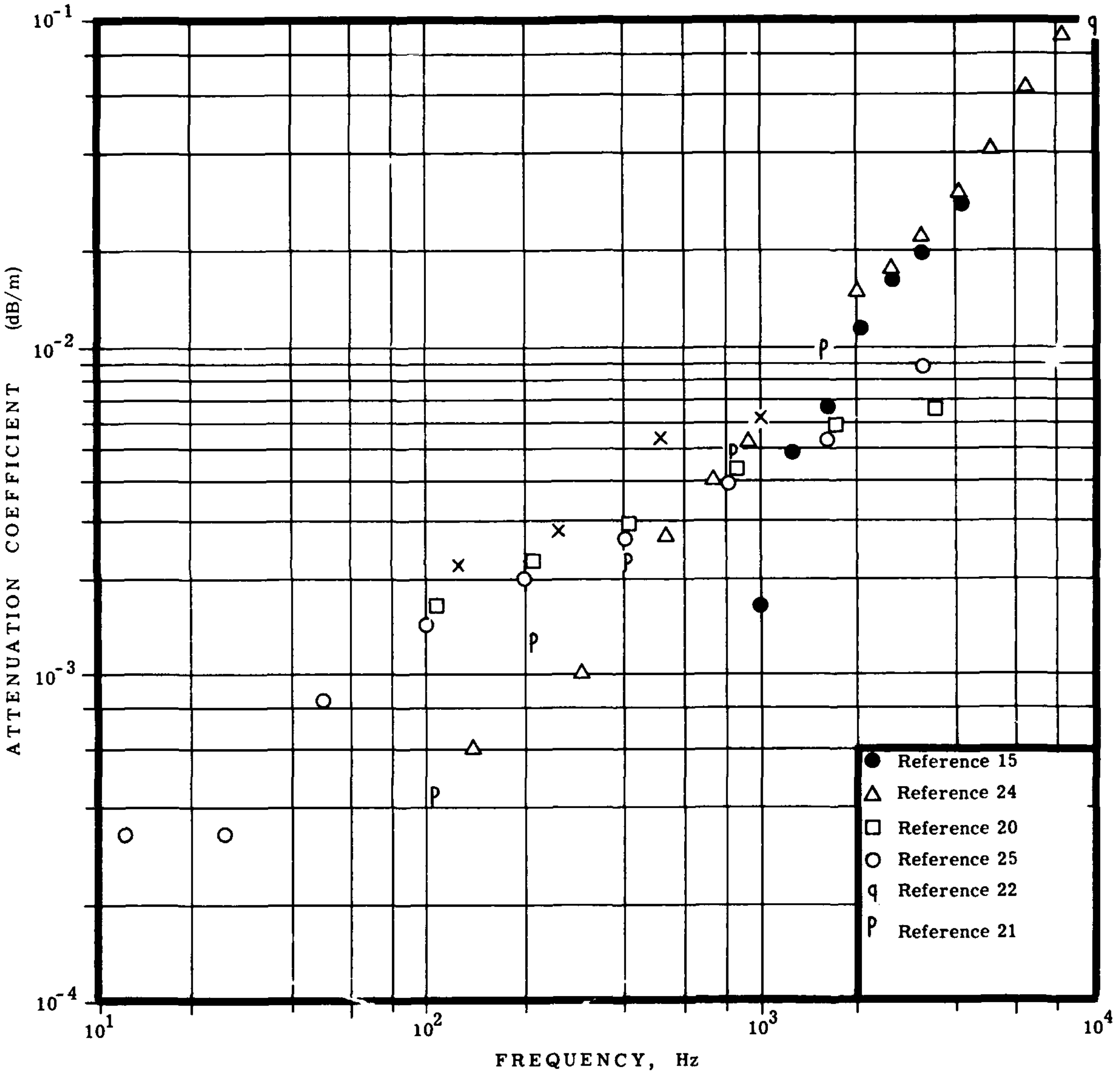


Figure 7-15 Excess Attenuation versus Frequency

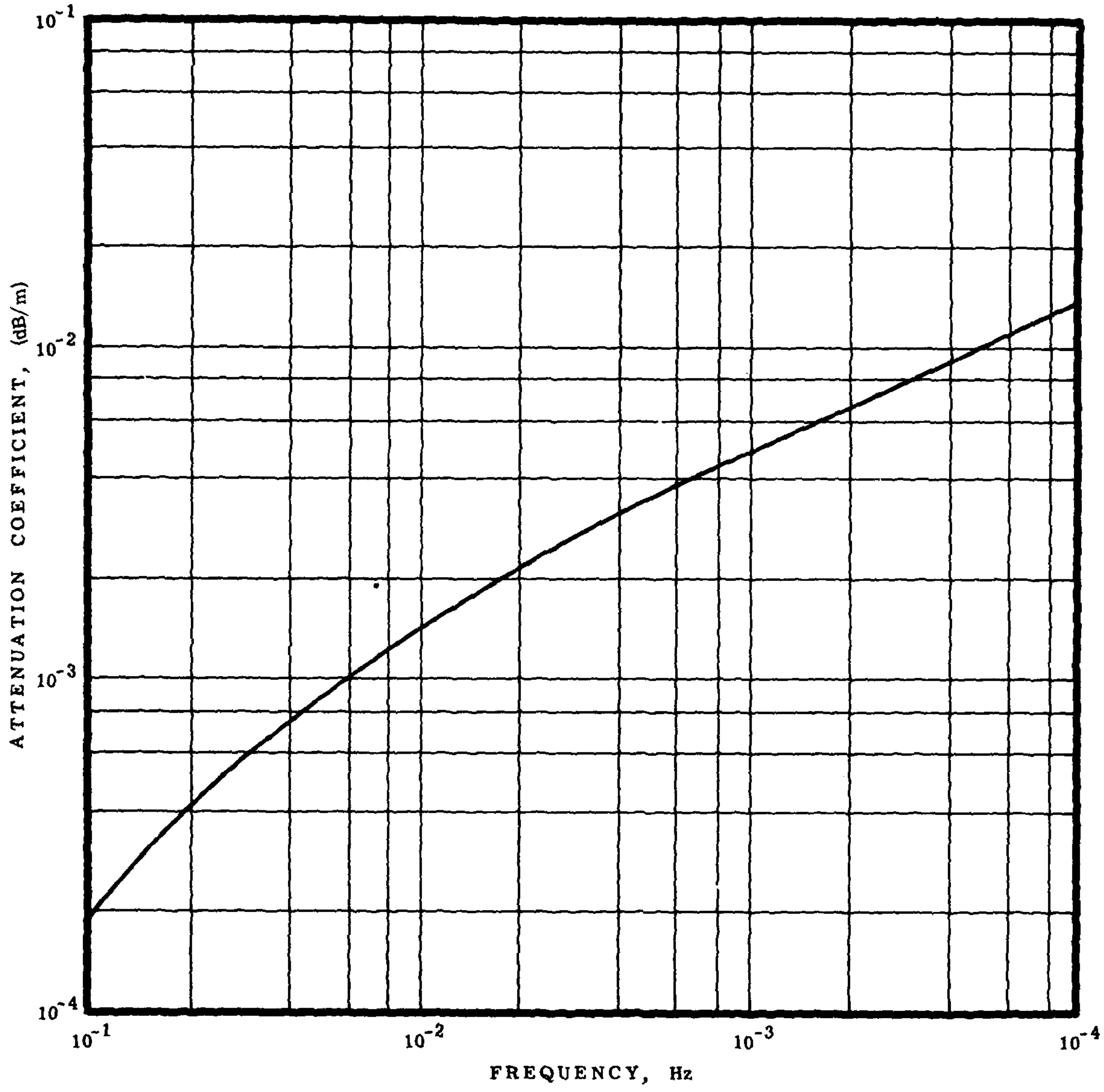


Figure 7-16 Excess Attenuation, Air-to-Ground versus Frequency

The next major effect of the atmosphere is refraction of the acoustic energy from the highly directional sound source. The directivity characteristics of the source in the vertical plane must be considered. Refraction occurs when meteorological conditions are such that the speed of sound (due to temperature and/or wind profiles) increases with altitude. This refracts the sound energy, resulting in higher levels, at a given point, than those which would be expected for a homogeneous medium. From all indications, the speed-of-sound profile characteristics of only the lower atmosphere (i.e., at altitudes less than 5,000 feet) are effective in the return of sound energy to the ground. If the speed of sound (due to temperature and/or wind profiles) decreases as a function of altitude, a shadow zone, or area of decrease in sound energy, should be noticed somewhere in the far-field. However, from past experience, it has been observed that because of wave length effects, dispersion due to turbulence, etc., the characteristics expected from the atmospheric conditions described above sometimes will not occur and, paradoxically, the level approaches that expected for a homogeneous medium.

A modified ray acoustic method coupled with the directional properties of the source in the vertical plane can be used to compute the intensity level for conditions of refraction. This technique is used to calculate the meteorological factor, M_f, in Equation 7-3 discussed earlier. For the special case where the cross-sectional area of a hypothetical ray tube approaches zero, a caustic or focal point is created. For this condition of refraction, the above method will predict an infinite intensity which is, of course, not physically possible. An "Airy" function, or some other technique can be used to distribute the energy around the focal point.

From experience it is known that sound pressure at indicated focal areas can be physically significant with levels increased on the order of 20 dB. It is of great benefit to know where focal zones will occur for given meteorological conditions even if the exact levels cannot be predicted with great accuracy. If indications are that they will be in highly populated areas of surrounding communities, then scheduled rocket firings can be postponed until more favorable conditions prevail.

For the Kennedy Space Center area, where space vehicle launches are frequent, the meteorological conditions which cause focusing are known to occur, but are not prevalent (reference 27). This is certainly an aid to minimizing the environments for the communities around the launch area. Figures 7-17 and 7-18, however, show two speed-of-sound profiles for typical conditions where refraction would produce increased levels at varying far-field locations.

7-2.2.2 Ground Plane Effects. The ground plane acts both as a reflecting and absorbing plane. The amount of reflection in general can be calculated based on known characteristics of the surface. The controlling parameters are the relative geometric arrangement of the source, ground plane, and receiver. Additionally, the frequency of the sound, the incident sound energy, and the absorption coefficient for a given frequency range govern the amount of energy reflected. Also the geometry will permit constructive and destructive interference patterns typical of wave phenomena. Assuming the ground plane to be a perfect reflector increases the overall power level of a source by 3 dB.

The presence of the ground plane, or any other reflecting surface such as a building, engine support structures, etc., will interfere with the acoustic field at the measurement location and distort it from its free-field natural state (i.e., with no obstructions present).

The diagrams presented in Morgan, Southerland, and Young (reference 28) indicate the phenomenon of reflection and its effects. The geometry and the resulting effects, shown in Figure 7-19, are applicable to an ideal reflecting surface. Other surfaces are handled similarly with consideration of absorption or ground impedance effects.

Acoustic data measured in the field often show reflection effects. The measured data must be corrected to accurately estimate the sound source characteristics.

In the near- and mid-field areas, one of the problems in using the reflection theory is to find the apparent location of the sound source in the flow field for use in determining geometry conditions. This problem exists because the true source is spatially extended. The apparent location of the source of a particular frequency could be assumed in an attempt to analyze reflection effects in the data. In such cases, this is difficult because the assumed distribution of sound sources in a jet exhaust flow are not uniquely defined.

When data taken from several field measurement locations presented in spectral form exhibit effects due to interference phenomenon, these data can then be used to work backward to bound a general region of the jet appearing as the sound source for a given frequency. All such considerations must be taken into account when evaluating, analyzing, and using data to determine free-field source characteristics and when generating detailed environmental estimates.

The ground plane, being a boundary with respect to the sound source and the sound propagation, also has certain ground cover effects which influence the sound received at far-field positions. A snow cover on the ground has a very noticeable quieting effect. Although the quieting effects of other forms of ground cover are not so obvious, they are of concern in areas where high level noise may be a problem to a community. The noise problem would be generally much worse if it were not for the contributing factor of additional sound energy absorption by such ground cover as trees, brush, grass, etc. Just as the conditions of the atmosphere effect the propagation, in that more sound is absorbed for certain meteorological conditions, likewise the ground plane cover and its absorption effects vary, both regionally and seasonally, and with a great many other factors.

Acoustic data measured in the far-field inherently have ground absorption effects in them. If these are significant, the problem of describing or using the measured data to arrive at the sound source characteristics must be highly qualified and used with caution. The frequency range affected depends on the type of cover; these effects are thought to be broader if there is a complexity of cover; i.e., a mixture of bushes, trees, grasses, etc. When the ground is bare or with short grass, the portion of the spectra affected appears in the higher frequency range.

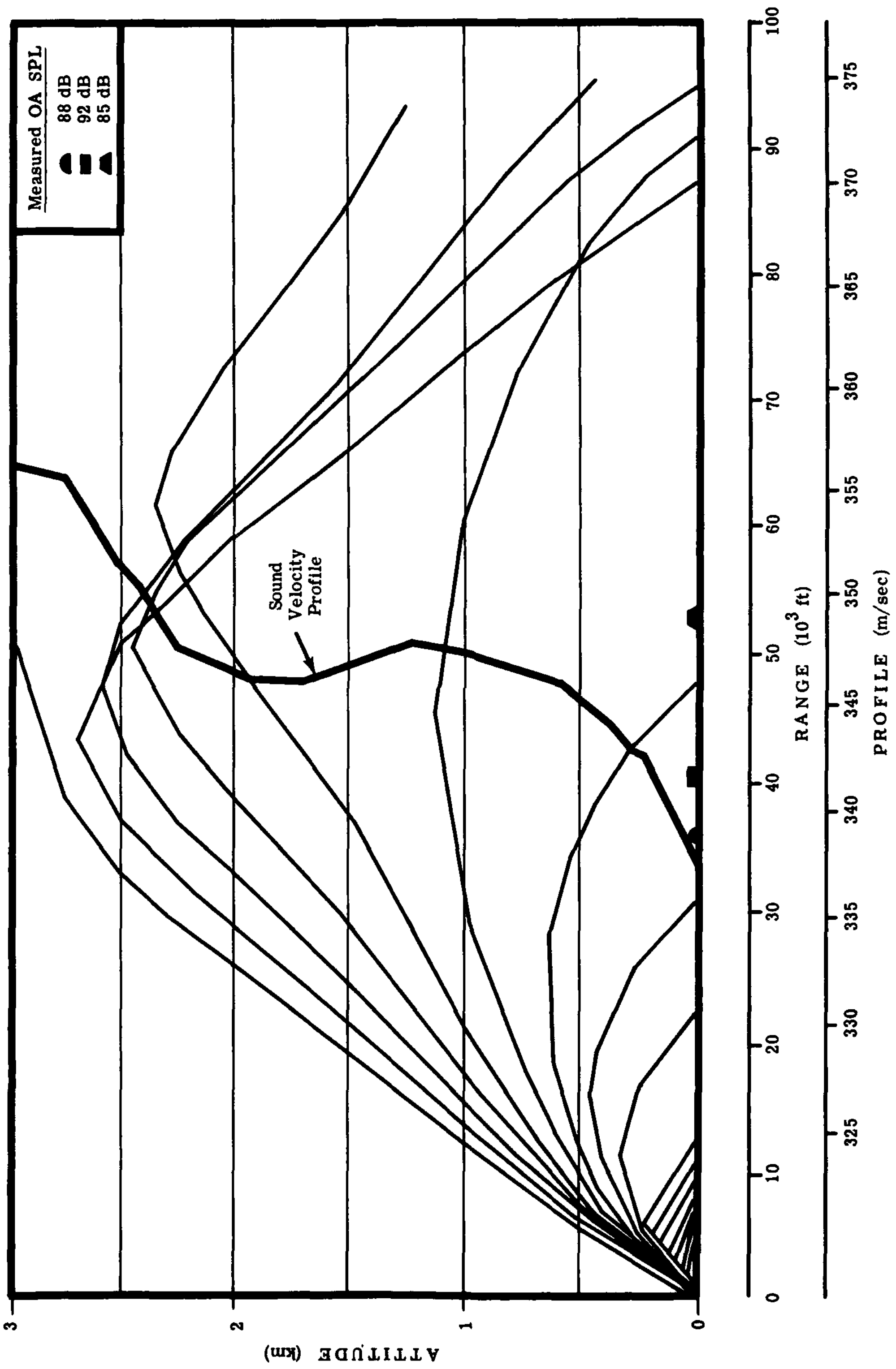


Figure 7-17 Typical Acoustic Ray Path (F-1 Engine Firing)

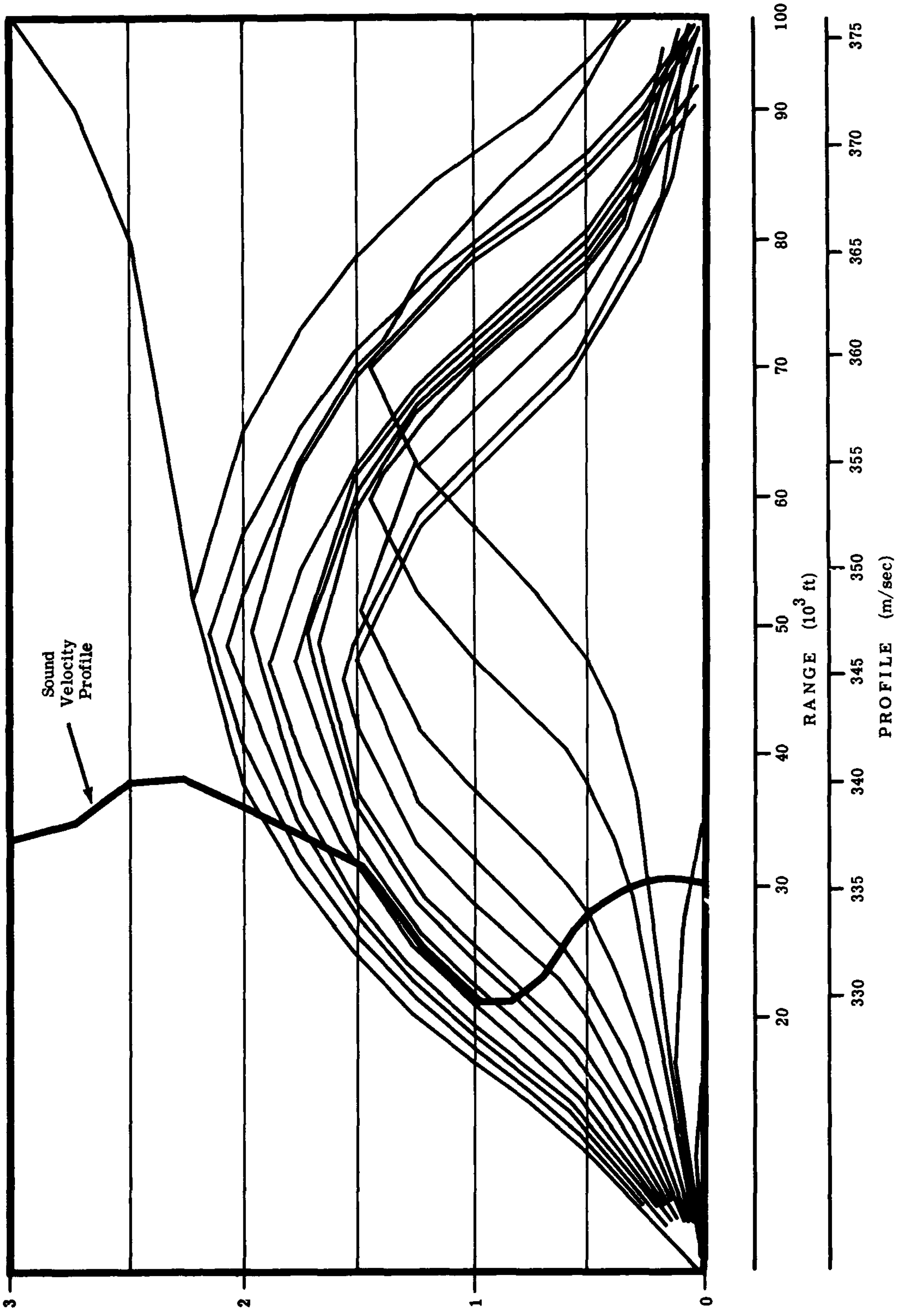


Figure 7-18 Typical Acoustic Ray Paths

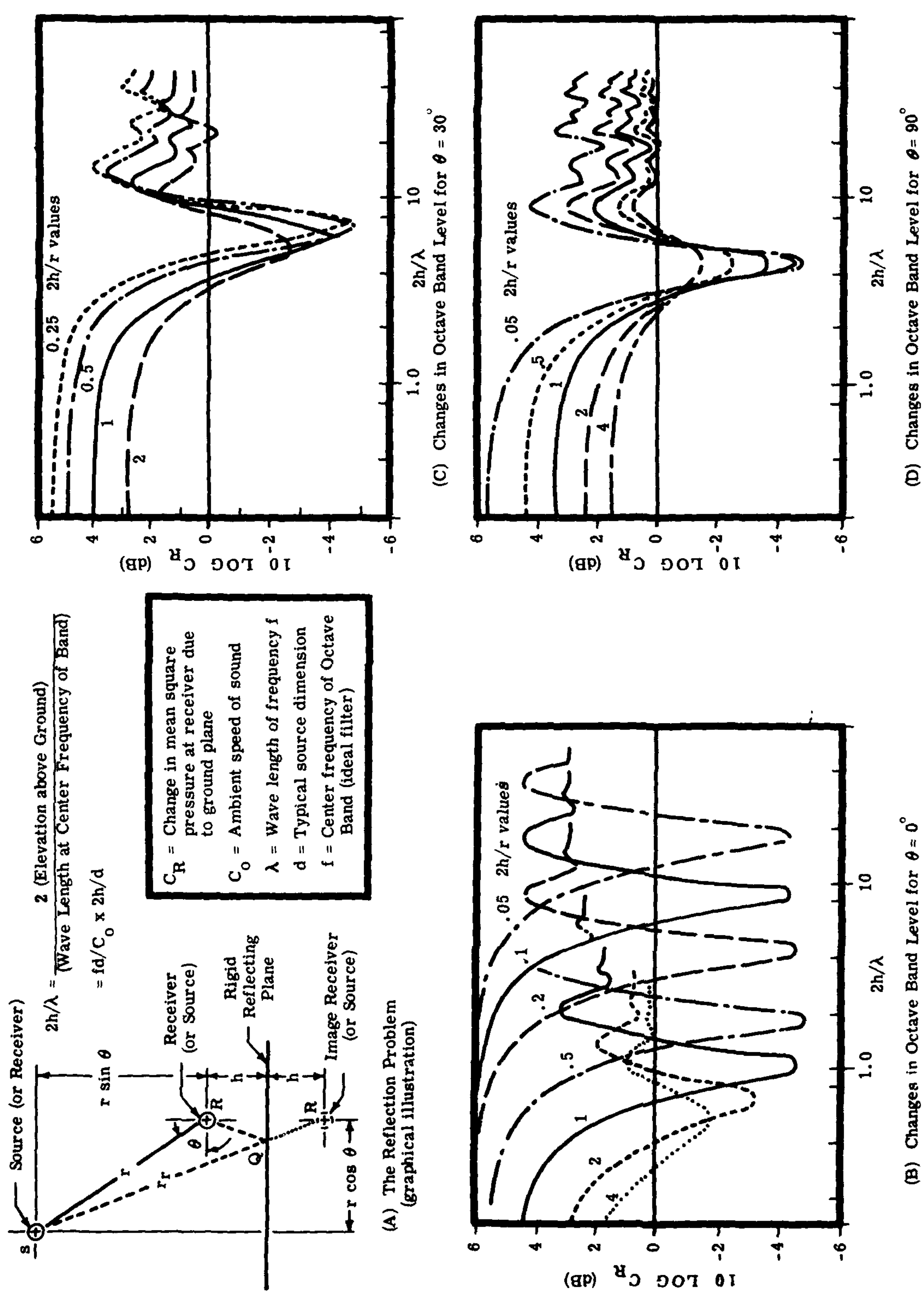


Figure 7-19 Changes in Octave Band Levels at a Point Due to the Presence of an Ideal Reflecting Surface

If it is considered necessary to apply the absorption characteristics of ground cover conditions, observed average conditions and their resulting absorption values are usable in most cases for rough estimates. These data are available in the references; the data most appropriate to the problem should be used.

7-2.3 TYPICAL ACOUSTIC ENVIRONMENTS FOR ADVANCED VEHICLE CONFIGURATIONS. The acoustic environments developed by the engine exhaust flow for the next generation of space vehicles, i.e., Saturn V Modified Launch Vehicles (MLV), etc., are to become more intense because of the increased propulsion required. The environments will be similar to those produced by their predecessors, only higher acoustic pressures and slightly shifted energy spectra will evolve because the greater engine size or larger number of engines will increase the total mechanical power or available mechanical energy to be converted to acoustic energy.

Typical acoustic environments of two advanced Saturn V vehicle configurations have been estimated by application of the previously discussed techniques. As pointed out earlier, current prediction techniques depend to a great extent upon the principles of similarity; therefore, the environmental estimates presented were derived with this consideration in mind. An example of the far-field acoustic environments (reference 11) produced by a Saturn V strap-on configuration are presented in Figures 7-20 through 7-23. This configuration consists of a Saturn V core vehicle with four 156-inch diameter solid propellant thruster units strapped to the S-IC booster. The booster yields 7.5 million pounds of thrust and each strap-on unit yields 6 million pounds thrust. The total thrust is 32 million pounds (142.3 x 10^6 newtons).

Figure 7-20 presents the predicted far-field ground acoustic environment in time history form for various distances during launch. The maximum ground environment for the various distances can be seen to occur at progressively later times from lift-off as the distance increases. This fact is primarily due to the directivity of the source. Focusing or refraction of the acoustic energy are not considered in this example. A homogeneous isentropic propagation medium is assumed, along with the normal divergence effects, and the energy losses due to molecular absorption.

Figure 7-21 indicates the maximum overall sound pressure level anticipated for the ground plane at various distances from the launch site. Figure 7-22 presents the maximum octave band spectra, based on the overall sound pressure level, for a distance of 4.5 km (15,000 feet) from the launch site. The attenuation of the higher frequency energy absorption effects at this distance makes the octave band spectra peak at approximately 20 Hz. Figure 7-23 is a similar spectrum anticipated for 16.5 km (55,000 feet).

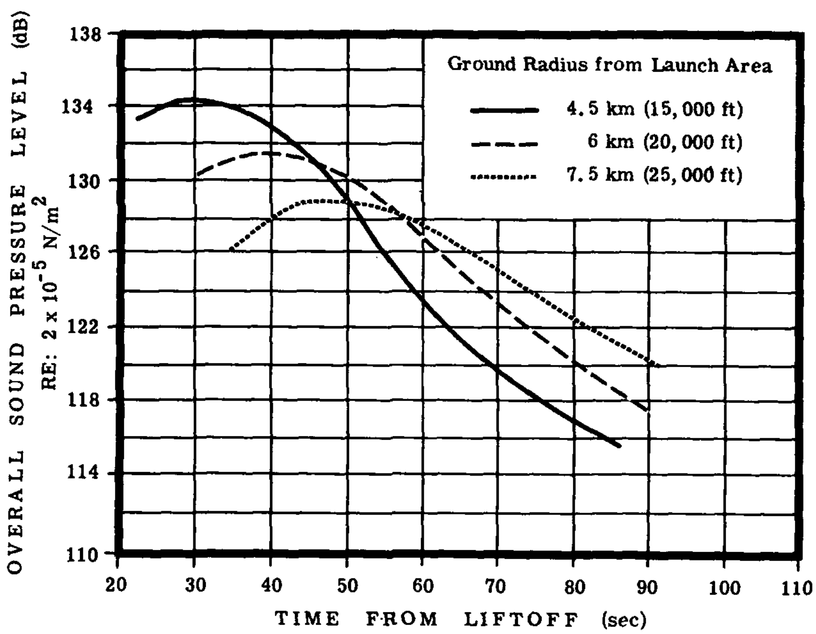
The acoustic environments for the space vehicle itself, for on-pad for a similar solid propellant strap-on configuration employing four 120-inch diameter solid propellant strap-on units are presented in Figure 7-24. This configuration consists of 7.5 million pounds thrust for the S-IC, the Saturn V booster stage, and 1.4 million pounds thrust for each of the four strap-ons, with a total thrust of 13.1 million pounds. Spectrum 1 of Figure 7-24 represents the octave band spectrum and overall sound pressure level for the portion of the vehicle less than one caliber from the engine exit nozzle plane, i.e., less than one diameter (33 feet) of the booster stage from the nozzle plane. Spectrum 2 of Figure 7-24 represents the octave band spectra and overall sound pressure level at five calibers (approximately 165 feet) above the nozzle plane. Spectrum 3 of Figure 7-24 represents the octave band spectra and overall sound pressure level approximately 10 calibers above the nozzle plane (330 feet). Usually, the predictions are within ± 2 to 3 dB of the measured values unless an unconventional deflector geometry or other factors influence the flow and, consequently, the resulting environment.

Acoustic environments for other advanced vehicle configurations involving conventional engines can likewise be computed within reasonable accuracy from the known parameters of geometric and operational characteristics. However, designs involving extreme engine operational parameters or other exotic engine configurations may influence the acoustic environments in such a manner that the existing prediction curves may not be considered valid. In these cases, each configuration must be evaluated by experiment and new normalized curves generated before any confident predictions from the present state-of-the-art can be made.

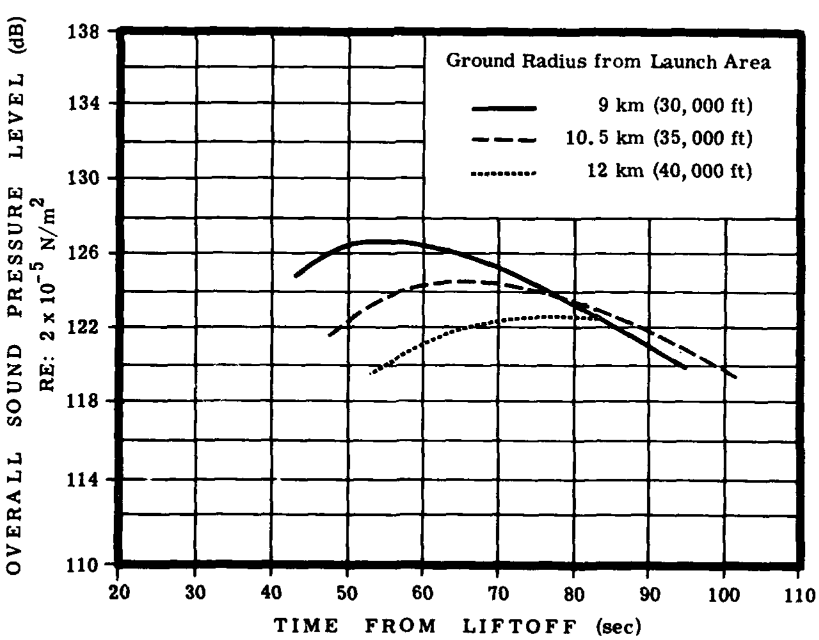
7-2.4 SOUND SUPPRESSION. Concerned with the intense acoustic environmental problems along with the structural dynamicists and ground support equipment designers, are the safety offices and the legal departments who become involved in community response issues where actual dwelling damage, aggravation, and nuisance claims are made. These types of problems have been emphasized recently with respect to airport noise problems created by current and future jet aircraft. The most practical and logical solution to these problems is to study directly the mechanisms of the generation of sound by hot exhaust flow fields and to reduce the acoustic energy output at the source itself; i.e., cure instead of fix.

There are many ways to approach the suppression task. One way is to determine the dominating noise-generating mechanisms contributing to the radiated acoustic energy and to alter the flow or geometry to minimize the acoustic efficiency of these mechanisms. Another technique often used in aircraft is to shift the energy spectrum to a higher frequency region where far-field problems at least would be alleviated to some extent because of the significant sound absorbing characteristics of the atmosphere in the higher frequency range. However, the near- and mid-field regions could suffer relative increases in the high frequency region which may be more objectionable and also be detrimental to the response of the rocket or jet structural components, (fuselage, vehicle skin surface, instrument units, astronauts, etc.). Other schemes involve operating the rocket flows at ideal expansion at sea level, etc., but all have limitations and in general are not considered successful. For example, the operation of rockets at ideal shockless expansion at sea level is not the optimum mode of operation with respect to optimum vehicle performance.

Other rocket engine suppression techniques have



(A) Ground Radius, 4.5–7.5 km



(B) Ground Radius, 9–12 km

Figure 7-20 Predicted Maximum Overall Sound Pressure Level Time History for Various Ground Stations for the Saturn V MLV Launch 32.0 x 10^6 lb Thrust

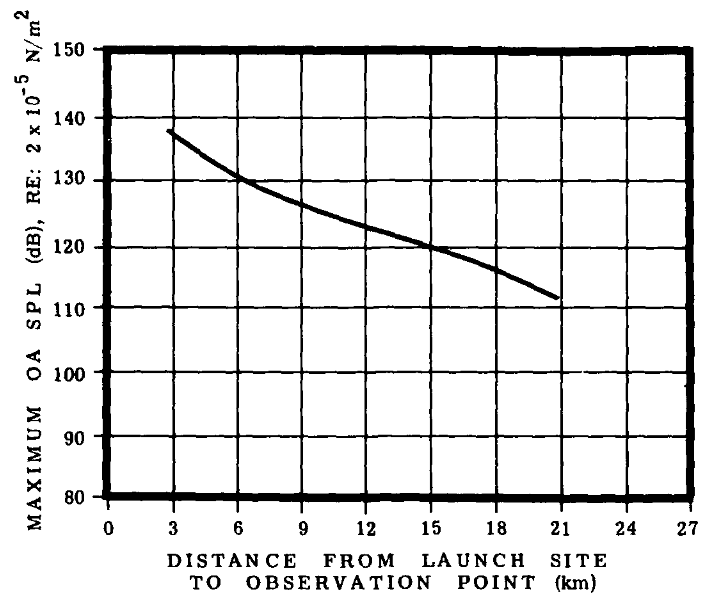


Figure 7-21 Maximum Anticipated Overall Sound Pressure Level for a Saturn V MLV Configuration of 32.0 x 10^6 lb Thrust versus Distance from Launch Pad

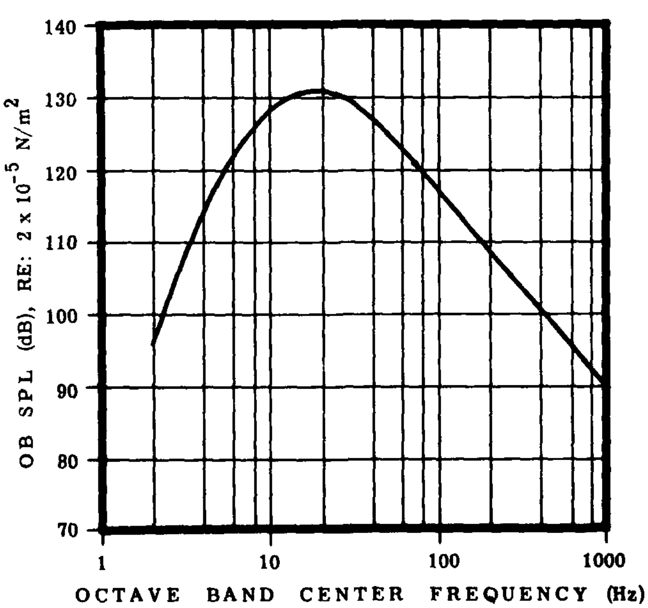


Figure 7-22 Predicted Octave Band Sound Pressure Level Spectrum at 4.5 km (15,000 ft) from Saturn V MLV Launch 32.0 x 10^6 lb Thrust

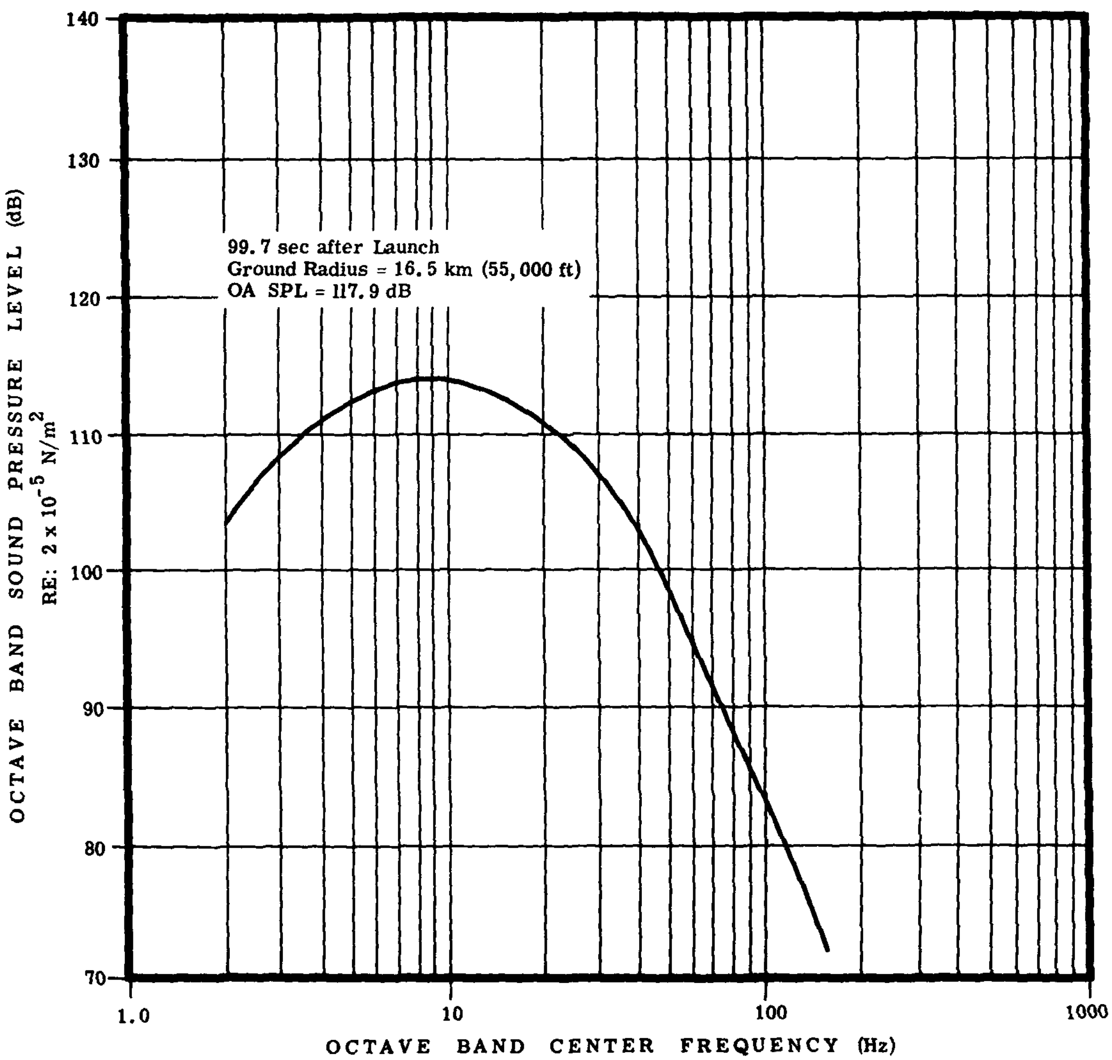


Figure 7-23 Predicted Octave Band Sound Pressure Level Spectrum at 16.5 km (55,000 ft) from Saturn V MLV Launch 43.0 x 10^8 lb Thrust

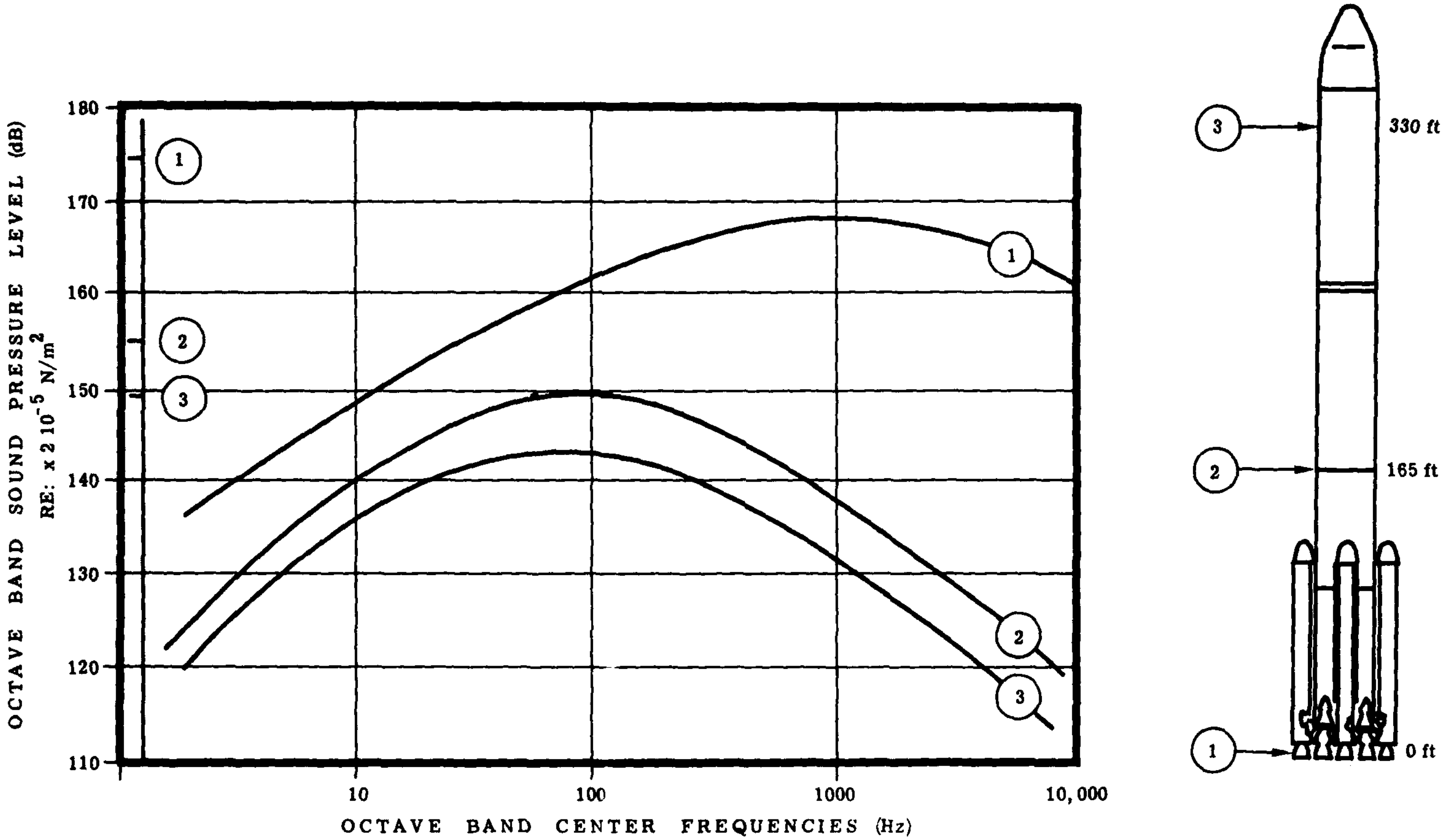


Figure 7-24 Predicted Acoustic Environments (Spectra for Three Vehicle Stations) for a 13.1 Million Pound Thrust Vehicle Configuration - A Saturn V with Four 1.4 Million Pound Thrust Solid Propellant Strap on Units

been tried for static firing conditions in the form of energy conversion by mixing the exhaust directly with water or through various tunnel configurations with water present for conversion to steam. Such attempts are aimed at reducing the kinetic energy of the final exit flow. This latter suppressor scheme (reference 29) (Figure 7-25) has proved very effective in reducing the sound energy without compromising effects, such as shifting of energy to other frequency ranges, moving the source to another location, etc. These studies were done on a model scale. However, when sound suppressor structures are scaled up to a full-size Saturn V, they would cost millions of dollars, and would require extremely large unrealistic suppressor structures; e.g., from reference 28, the suppressor volume would be 26 million cubic feet. This is impractical for large boosters. The former method of just mixing water directly with the flow field requires about a ten-to-one flow ratio of water to exhaust to obtain significant reduction. This, again, is highly impractical for large boosters because of their extremely high exhaust flow volumes.

Although the advantages of sound reduction by the tunnel approach for static tests of rocket engines are certainly evident, the advantage of the tunnel suppressor attachment is lost in its application to the launch vehicle operation. The suppressor will be effective only for the period of time that the vehicle is on the pad; lift-off would then expose the surroundings to the noise of exhaust flow. The application of such a full-scale suppressor, though apparently advantageous, is impractical in size and cost for static test cases, and is not considered feasible for launch at any cost.

It is felt that concentrated efforts should be sustained to determine the basic noise generating mechanisms of hot rocket exhaust flows, both deflected and undeflected. Once these mechanisms are fully or even partially understood, the development of practical techniques for suppression of noise from rocket and jet engines will be put into proper perspective and hopefully significant reductions without prohibitive penalties can be realized.

7-3 ASSESSMENT OF ACOUSTIC ENERGY HAZARDS (TO MAN) (References 30 to 32)

This part of Chapter 7 is concerned, primarily, with the definition of the hazards to which man is subjected by the pressure of airborne acoustic energy (sound waves or noise) in his working or living environments. The term, "acoustic energy hazard," is here used to mean any adverse effect imposed on man by the presence of any sound (noise) field. Such acoustic energy hazards may range from bodily injury through performance impairment down to simple perception of the presence and annoyance with the sound intrusion into an environmental area where quiet (no noise) is expected. The effects of sound waves on man and man's expected responses are related to and can be predicted, with a certain degree of assurance, from the physical specification (description) of the sound field when combined with information which states the "time spent in the sound field" by the exposed individuals. These numerically specified values of the physical parameters of the sound field and the exposure time, when related to man's responses (effects on him), become the criteria used to estimate (or predict) the probable effects of any particular sound field (from any particular source) on the exposed persons. Often, the physical specifications of the sound field will use specially weighted numerical values to improve the descriptions of the human responses (to better relate the sound stimulus to the response) as the properties of the sound fields vary and the durations of exposure change. The criteria for "acoustic energy hazards" will be stated and their use in the evaluation of the sound fields generated by chemical rocket propulsion systems illustrated by relating the criterion values to the numerical specifications of the acoustic fields of some commonly used systems. Most attention will be devoted to the primary acoustic fields generated by rocket systems but some attention will be given to secondary sound fields generated by the responses of structures to the rocket engine sound fields. Some general guidance will be given on the use of the criteria in assessing the effects on man of sound fields from support equipment and installations. Use of the criteria in planning installations, facilities and operations will be discussed and illustrated.

Chemical rocket propulsion systems generate acoustic energy (sound waves or noise) fields that encompass an unusually wide frequency spectrum. Frequency components, that contribute significant portions of the total acoustic energy, range from below 1 Hz to well beyond 100,000 Hz. Thus, these sound fields contain energy in the infrasonic (sub-audible) frequency region, below 20 Hz; in the audible (or audio) frequency region from 20–20,000 Hz; and in the ultrasonic (frequencies above the high frequency detection range of the human ear) frequency region from 20,000 Hz to well above 100,000 Hz. Supporting equipment and facility, acoustic energy sources usually generate a narrower acoustic frequency spectrum with major portions of the acoustic energy confined to the audible (audio) region, 20–20,000 Hz. Therefore, the total frequency range over which our criteria for the effects of acoustic energy on man are needed is quite extended and, in fact, includes frequency regions for which current criteria are extremely tentative. Similarly the intensity (strength, energy level) range of the acoustic fields (of interest) is extremely large, again almost exceeding the intensity range for which criteria have been developed. When one also considers the range of durations of exposure, in addition to the frequency and intensity ranges, applicable to the many different work situations related to manufacture, handling and operation of chemical rocket propulsion systems, he is again confronted by significant uncertainties. Most data, available today, apply to regular, nominal 8 hours daily exposures over a five day work week. However, many exposures from rocket engine sound fields are of short duration and often separated from each other by one to many days. In view of all the factors just described one must realize that the criteria presented herein will usually be tentative and often borderline extensions from more firmly based criteria. The criteria will be grouped by subdivisions of the frequency range because of the degree to which human responses (effects on man) are frequently dependent.

7-3.1 LOW FREQUENCY SOUND (NOISE), 1–100 Hz.

This part of the sound frequency spectrum is steadily increasing in importance as propulsion systems are developed to deliver ever greater amounts of thrust.

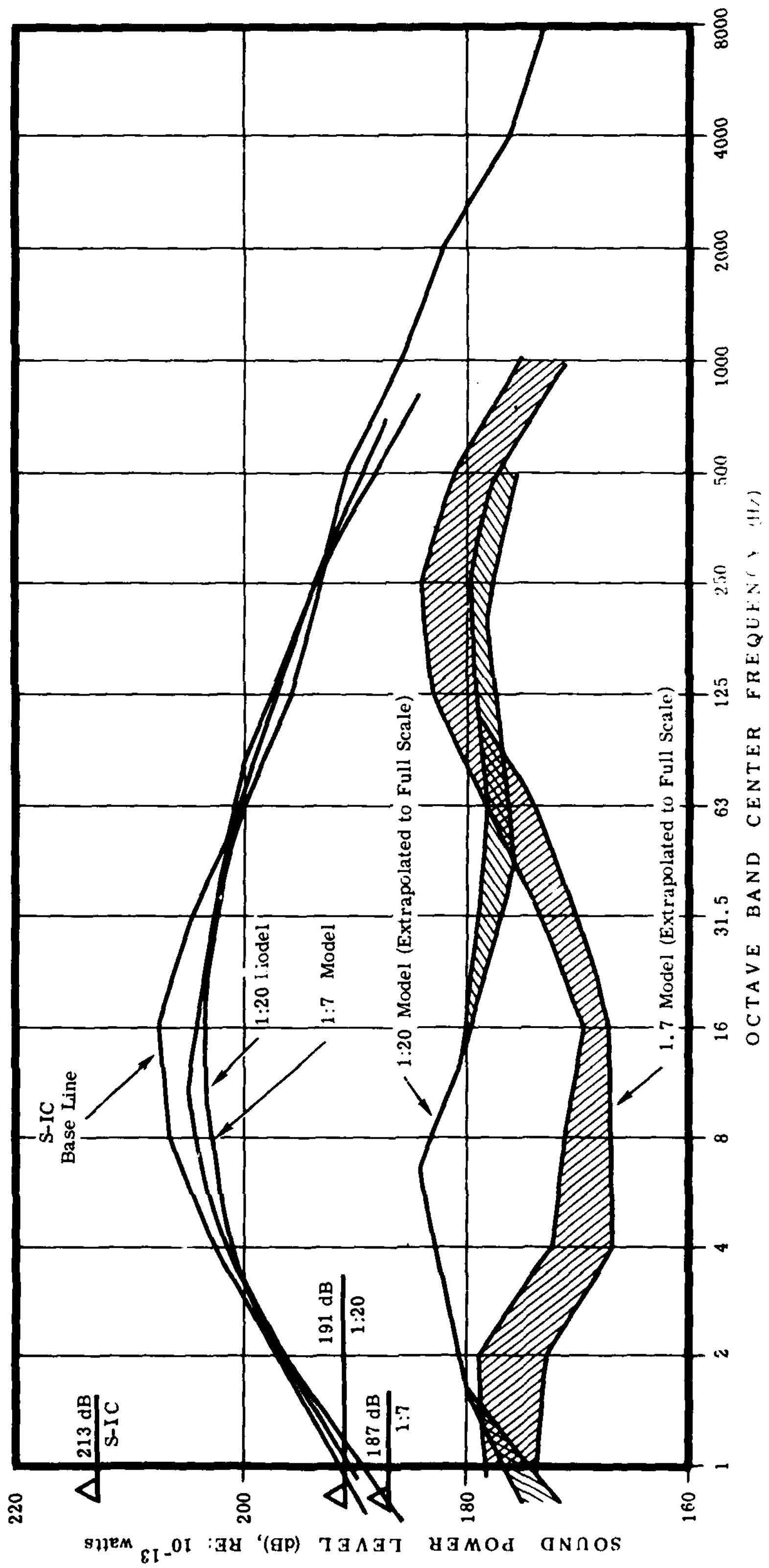


Figure 7-25 Acoustical Performance of the S-IC (Saturn V Booster Stage) Sound Suppressor as Scaled-Up from Model Performance

Figure 7-5 presents data on the sound spectrum at a ground position 5000 feet from the Titan vehicle. Observe that an octave band, centered near 20 Hz, exhibits the highest band, sound pressure level. Figure 7-22 portrays the predicted octave band spectrum for a ground position 15,000 ft from a Saturn V, MLV launch. Again, the highest octave and sound pressure level is found in the band centered just below 20 Hz. Figure 7-23 displays the estimated octave band pressure levels for a position 55,000 feet from a Saturn V, MLV launch and the band showing the highest pressure level is centered below 10 Hz. Other measured sound pressure levels, at various distances from a Saturn V launch, (from 600 to over 70,000 feet) show maximum band pressure levels in the bands centered around 2, 4, and 8 Hz and, depending on the location, these band pressure levels range from 110 dB to well over 150 dB. Furthermore, depending on the operation and on the location, with respect to the launch pad, a similar range of octave band pressure levels is found for all octaves up to a center frequency of 125 Hz. Now, given these sound fields, the question is, what do the criteria say about them? In order to manage the criteria in a reasonable manner, this frequency range will be subdivided into two (2) ranges: (1) the infrasonic (sub-audible) range 1–20 Hz, and (2) the audible part of this range, 20–100 Hz.

7-3.1.1 The Sub-Audible Range, 1–20 Hz. The higher octave band, sound pressure levels cited above, (150 dB and higher) suggest that these sound fields would cause pain, localized near the eardrum, if the bands were in the frequency range 50–2000 Hz. Let us now determine the human response to be expected in the frequency region 1–20 Hz. One set of data on the pain threshold for pure tones in the frequency range 3–20 Hz is presented in Figure 7-26. At 20 Hz the pain threshold is near 140 dB (perhaps a little above). Exposure to frequencies near 10 Hz produced the pain sensation near 148 dB and at 3 Hz the pain threshold was reached at 160 dB or just above. Under exposure to static pressure the pain threshold was reached at or just below 180 dB. In these experiments the sound pressure levels were increased steadily until the pain sensation was evoked and reported, then exposure ceased. All of the exposures were of short duration but each actual duration was determined by the time the subject used to decide "pain is present". Some additional data on man's response to sounds in the frequency region 1–20 Hz are shown in Figure 7-27, particularly tests 9, 10, 11 and 15. In test 15 the subjects were exposed to discrete frequencies of 1, 3, 5, 6 and 7 Hz at a sound pressure level of 150 dB and to frequencies 8, 9 and 10 Hz at a level of 145 dB; also exposure was made to the frequencies 11, 12, 13, 14 and 15 Hz at a level of 140 dB. Test 9 involved exposure to a narrow band of noise, centered on the frequency 2 Hz at a pressure level of 150 dB. Test 10 was a similar exposure to a band centered on 5 Hz at a level near 148 dB and in test 11 the band was centered about 10 Hz and the band pressure level was about 143 dB. All exposures in tests 9, 10, 11, and 15 were for 2 minute periods. In these experiments no subject reported ear pain; without protective devices one subject reported an occasional tickle sensation localized near the eardrum; without protection, the most commonly perceived effect was "an uncomfortable sensation reflecting pressure build-up in the middle ear, which required frequent valsalva to relieve." Earplugs or earmuffs prevented the middle ear pressure changes. In general, all subjective sensations were reported to increase rapidly as the sound pressure level was increased above 145 dB. All subjects agreed that all these exposures were tolerable although not always pleasant; use of earplugs to prevent the middle ear pressure changes rendered these exposures "fully tolerable". No hearing threshold shift was detectable by tests conducted one hour after these exposures.

7-3.1.1.1 The Criteria 1–20 Hz. Based on the limited data now available, tentative criteria are proposed, as follows: Exposure to a sound pressure level of 150 dB, without protection, is acceptable over the frequency range 1–7 Hz; exposure to 145 dB is acceptable from 8–11 Hz and exposure to 140 dB is acceptable from 12–20 Hz. These pressure level values apply to discrete single frequencies or to octave bands centered about the stated frequencies. No single exposure shall exceed four (4) minutes and at least 24 hours shall elapse between two (2) consecutive exposures. The stated level is without protection but use of earplugs is recommended for all exposures to these levels because their use will reduce the unpleasant sensations. If extreme requirements exist, the stated sound pressure levels may be increased by 5 dB, if well fitted earplugs are worn during exposure. Exposure duration is unchanged. No extensions of these criteria to higher or lower frequencies are acceptable and no extension to higher sound pressure levels are to be made. These tentative criteria are subject to adjustment as additional data are acquired in the future.

7-3.1.1.2 Application of the Criteria, 1–20 Hz. The next significant question is: What influence will these criteria for the 1–20 Hz frequency range have on practical operations? Data from the 29 February 1968 revision of reference 12 shows sound pressure levels of 158± 2 dB for the octave bands centered on 2, 4, 8, and 16 Hz at distances between 200 and 300 feet from the launch pad during lift off. The sound pressure levels were around 150±3 dB for the same bands at points 600 feet from the pad and band pressure levels of about 145±3 dB were measured 1200 feet from the pad, while band pressures of 140±2 dB were measured about 2400 feet from the launch pad. During the same operations, at about 17,000 feet from the pad, band pressure levels were 115±2 dB for these bands; at approximately 31,000 feet the band pressure levels were 112±2 dB; at 69,000 feet they were about 105 dB and at 104,000 feet the levels were 76±13 dB for bands centered at 2, 4, 8, and 16 Hz. Examination of the data (above) shows that at 2400 feet (band sound pressure levels 140±2 dB) were below the criterion levels for all bands except that centered on 16 Hz. However, other hazards (for example, blast hazards) dictate the location of personnel at separation distances greater than 2400 feet during launch or the provision of suitable protective structures to house those persons at work. Therefore, the criteria should not impose real operational impediments. It is conceivable that the required 24 hours between exposures will affect operational plans but this restriction is also removed when distance or special structures provide adequate reduction of the sound pressure levels, that is, to band pressure levels below 135 dB.

No criteria were given for octave band pressure levels below 120 dB for this frequency region because

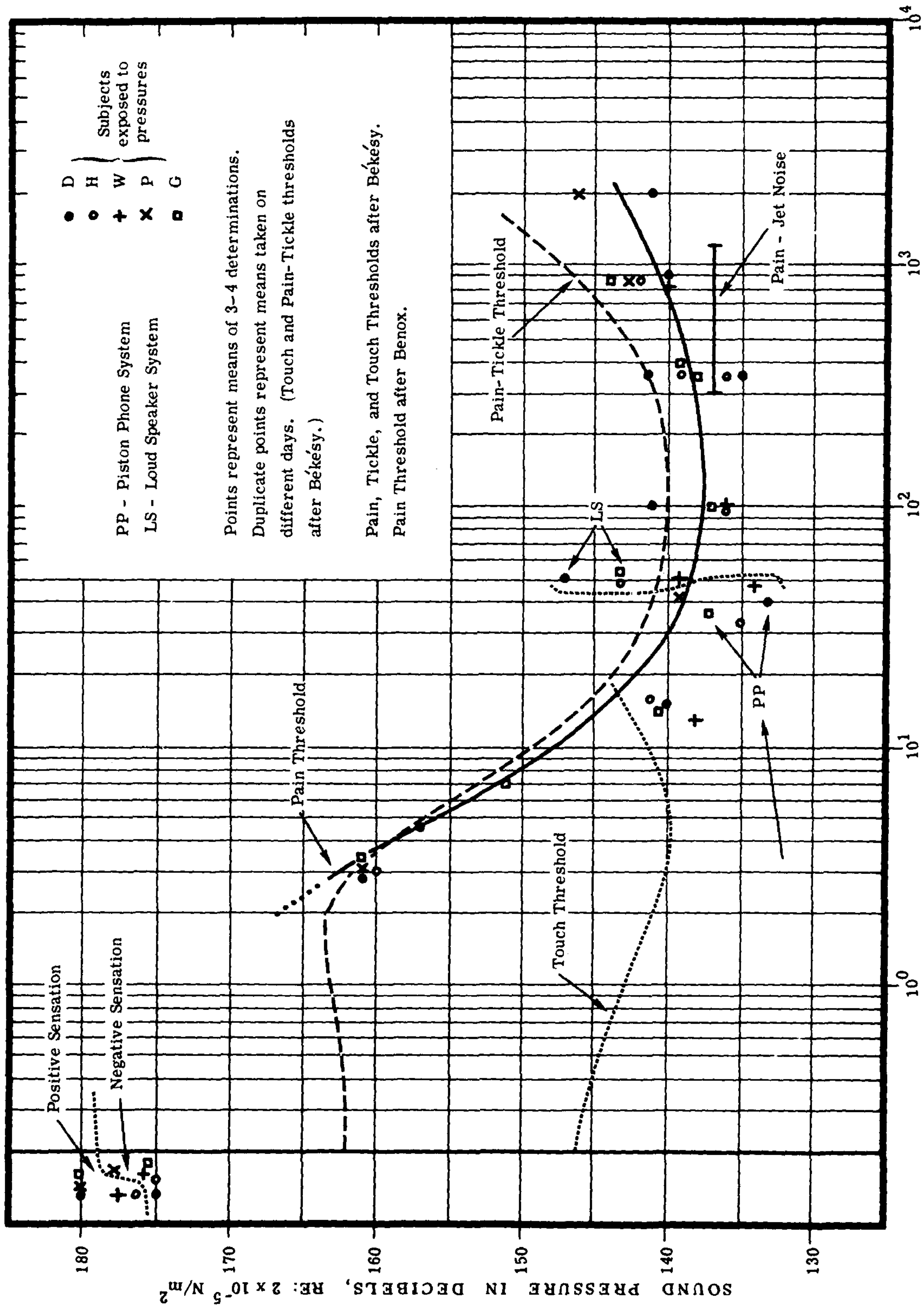


Figure 7-26 Thresholds for Aural Pain Produced by Pure Tones and Jet Noise

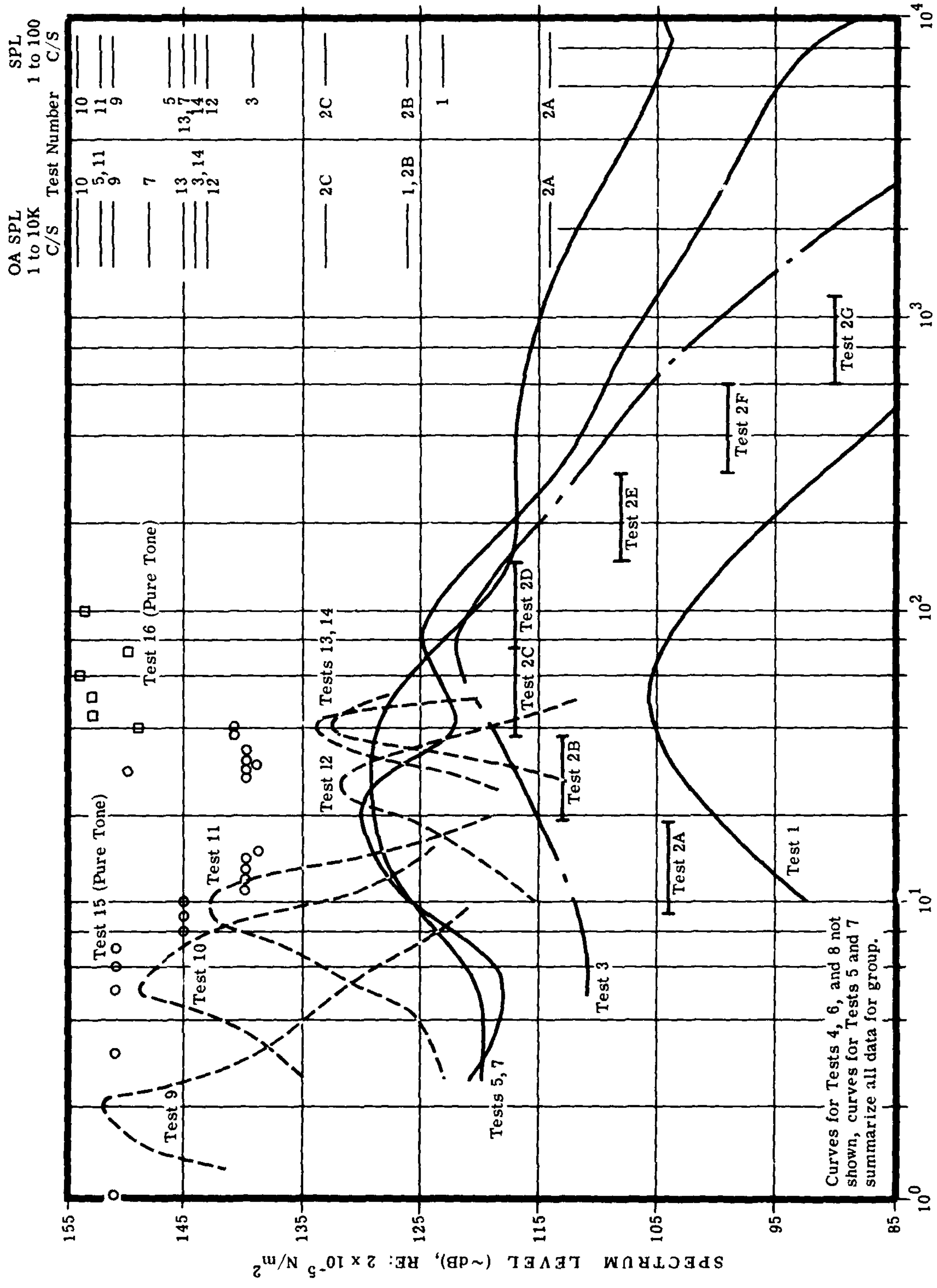


Figure 7-27 Summary of Test Environments

these frequencies alone do not contribute to understanding speech and will not interfere with conversation. It is possible, however, that band pressure levels above 100 dB may excite vibrations in structural components of houses or of their fixtures, fittings and furnishings. These secondary sources can be disturbing and could lead to annoyance if they recur frequently. However, there are no data on which to base criteria and none are now proposed.

7-3.1.2 The Audible Low Frequency Range, 20-100 Hz. Figure 27 shows the results of tests in this frequency region; test 15 covers the frequency range 25-40 Hz and test 16 provides data over the frequency range 40-100 Hz. The sound pressure levels from 135-140 dB were judged tolerable for the frequency range 20-40 Hz (test 15). The source capability limited the maximum exposure level at 40 and 43 Hz but voluntary tolerance limits were reached at 153 dB for 50 Hz; 154 dB for 60 Hz; 150 dB for 73 Hz; and 153 dB for 100 Hz. A decision was made to stop exposures to these levels for the time being because the following, subjectively alarming, responses were reported: mild nausea, giddiness, subcastal discomfort, cutaneous flushing and tingling occurred at 100 Hz; coughing, severe sub-sternal pressure, choking respiration, salivation, pain on swallowing, hypopharyngeal discomfort and giddiness were observed at 60 and 73 Hz. One subject developed a transient headache at 50 Hz; another developed both headache and testicular aching during the 73 Hz exposure. A significant visual decrement (both subjective and objective) occurred for all subjects during the 43, 50, and 73 Hz exposures. All subjects complained of post-exposure fatigue which was resolved by a night's sleep. No shifts in threshold of hearing were measurable two minutes after exposure; the earplugs and earmuffs worn apparently attenuated both the fundamental frequency and the higher harmonics adequately. Recovery from most symptoms was complete on cessation of exposure tests 5 and 7 and 12-14 spanned most of this frequency region (20-100 Hz) at levels between 125 and 135 dB and all these exposures were rated "tolerable" by all subjects even though moderate vibration of the chest wall was perceived. Data on pain threshold are shown in Figure 7-26; this threshold is reached at 20 Hz at about 142 dB and the threshold pressure level decreases as frequency increases to 137 dB at 100 Hz. No doubt pain was absent during tests 15 and 16 (Figure 7-27) because protective ear plugs or ear muffs were worn.

7-3.1.2.1 The Criteria, 20-100 Hz. This frequency band has received little attention, as regards the formulation of exposure criteria, in part, because it makes essentially no contribution to understanding speech signals and, in part, because the sound generation and measuring equipment usually available performs poorly in this frequency region. Based primarily on the data presented in Figures 7-26 and 7-27, as discussed before, the "tentative" criterion sound pressure level for both pure tones and octave bands is set at 135 dB without protective equipment and at 150 dB when wearing earplugs for exposure to this frequency region. The 135 dB value is just below pain threshold (Figure 7-26) and pain is usually considered to indicate "damage is being done." The 150 dB value is established to minimize the symptoms and signs described in Section 7-3.1.2, which led to voluntary termination of exposures in test 16 at the levels shown in Figure 7-27. The exposure durations of test 16 were not less than two minutes and short exposure periods of 2-4 minutes are specified for the 150 dB pressure levels. At the 135 dB sound pressure levels a single daily exposure lasting no longer than 20 minutes is specified by the criteria. These criteria apply to this specific frequency band (20-100 Hz) alone but one must remember that practical work operations usually involve exposure to other frequency bands at the same time and this fact will tend to lower the levels that exposed persons find acceptable.

7-3.1.2.2 Application of the Criteria, 20-100 Hz. It now remains to relate the stated criteria to practical work environments. Data in the February 29, 1968 revision of reference 12 show that sound pressure levels about 300 feet from the launch pad are around 152 dB over the frequency range 20-100 Hz; about 600 feet from the pad the pressure levels are 142±3 dB; around 1200 feet from the pad pressures were 145 dB at 20 Hz and decreased to 135 dB at 100 Hz; about 2400 feet from the pad the pressures were 142 dB at 20 Hz and dropped to 130 dB for 100 Hz. At greater distances from the launch pad the sound pressures over the range 20-100 Hz varied from 115-110 dB at 17,000 feet; 111-105 dB at 30,000 feet; 97-85 dB at 69,000 feet and from 78-73 dB at 104,000 feet. Comparing these data with the criteria show that at 300 feet from the launch pad the criteria are exceeded. However, persons working this close would be enclosed in protective structures which would attenuate the sounds. These data also show the need for a separation distance from the launch pad greater than 2400 feet for exposure without protection, but at this distance protective structures would probably be required for other reasons. Therefore, these criteria should not adversely affect usual operations. The same criteria values would apply to sound fields from any other source that might be used in the manufacture or installation of the rocket engine or the system it powers. Sound in this frequency range can also excite resonances in residential type structures and some problems arising from this cause may be anticipated out to distances of about 69,000 feet band pressure level 85-97 dB. Frequency of recurrence will be an important consideration and in most instances the number of firings may be small enough and sufficiently separated in time to minimize this problem. This frequency band (20-100 Hz) contributes essentially nothing to the intelligibility of spoken English and exposure to these frequencies, in the absence of higher frequency components, up to the criterion level of 135 dB, will not significantly impair the voice communications capability of men in any work area.

7-3.2 MIDDLE FREQUENCY SOUND (NOISE), 100-6300 Hz. This frequency band has been purposely selected for this chapter to span the frequency range, within the audible (audio) spectrum, that is of major importance for voice communication (conversation). This frequency region also receives primary consideration with respect to its potential for causing "noise-induced" hearing impairment as a consequence of human exposure to the noise (sound fields) of industrial work-environments. This frequency region also includes most of the frequencies of industrial and transportation system sound fields that contribute to the annoyance of residents occupying areas into which these sounds propagate. The criteria presented here are relevant to the three general areas of man's responses cited above.

7-3.2.1 Voice Communication in Noise. Sound fields (noise) containing all or part of the frequencies within the range 100–6300 Hz can, depending on the actual pressure level, interrupt completely or lower the proficiency of voice communications. Numerous procedures (of varying complexity) exist for assessing the degradation of communications capacity caused by the presence of sound (noise) fields but the criteria used herein are stated in terms of a rather gross but relatively simple assessment technique.

7-3.2.1.1 The Criteria–Voice Communication. The criteria are shown in Figure 7-28 in the form of curves showing band pressure level as a function of band center frequencies over the frequency range 63 Hz–8000 Hz. These noise criteria curves are frequently referred to as NC-Curves and the ones plotted cover the range NC-20–NC-70 in steps of 10. The interpretation of the NC-Curves is given in Table 7-3, which describes the communication environments associated with particular NC values.

Table 7-3

Noise Criteria for Offices and Work Spaces

Recommended Noise Criteria for Offices	Communication Environment
NC-20–NC-30	Very quiet office—telephone use satisfactory; suitable for large conferences.
NC-30–NC-35	Quiet office—satisfactory for conferences at a 15-foot table; normal voice 10–30 feet, telephone use satisfactory.
NC-35–NC-40	Satisfactory for conferences at a 6–8 foot table; telephone use satisfactory; normal voice 6–12 feet.
NC-40–NC-50	Satisfactory for conferences at a 4–5 foot table; telephone use occasionally slightly difficult; normal voice 3–6 feet; raised voice 6–12 feet.
NC-50–NC-55	Unsatisfactory for conferences of more than 2 or 3 people; telephone use slightly difficult; normal voice 1–2 feet; raised voice 3–6 feet.
Above NC-55	Very noisy office; environment unsatisfactory; telephone use difficult.
Recommended Noise Criteria for Work Spaces, Shop Areas, etc.	**Communication Environment**
NC-60–NC-70	Person-to-person communication with raised voice satisfactory 1–2 feet; slightly difficult 3–6 feet; telephone use difficult.
NC-70–NC-80	Person-to-person communication slightly difficult with raised voice 1–2 feet; slightly difficult with shouting 3–6 feet; telephone use very difficult.
Above NC-80	Person-to-person communication extremely difficult. Telephone use unsatisfactory.

7-3.2.1.2 Application–Voice Communication Criteria. One may question the existence of a voice communication hazard in association with the principal operations employing chemical rocket propulsion systems. This question arises because operating personnel are usually inside special structures designed to protect them from other hazards (blast, for example) and these structures attenuate the sound waves sufficiently to eliminate serious interference with voice communication. If, in any particular case, this is not true, the criteria given will permit a determination of the quality of voice communication that is possible. Outside the protective structures, but inside the facility boundaries, where personnel may safely work in-the-open, the duration of any single firing is so short that little communications impairment will result—besides, most of these persons wish to witness the big event and so do not care about voice communication at that time. Looking at the conditions outside the facility boundary one should again examine Figure 7-23 which portrays the sound field 55,000 feet from the launch site. The band pressure levels are: in the 63 Hz band—92 dB; in the 125 Hz band—77 dB; the level in higher bands is not shown but the curve is falling steeply. The level for the 63 Hz

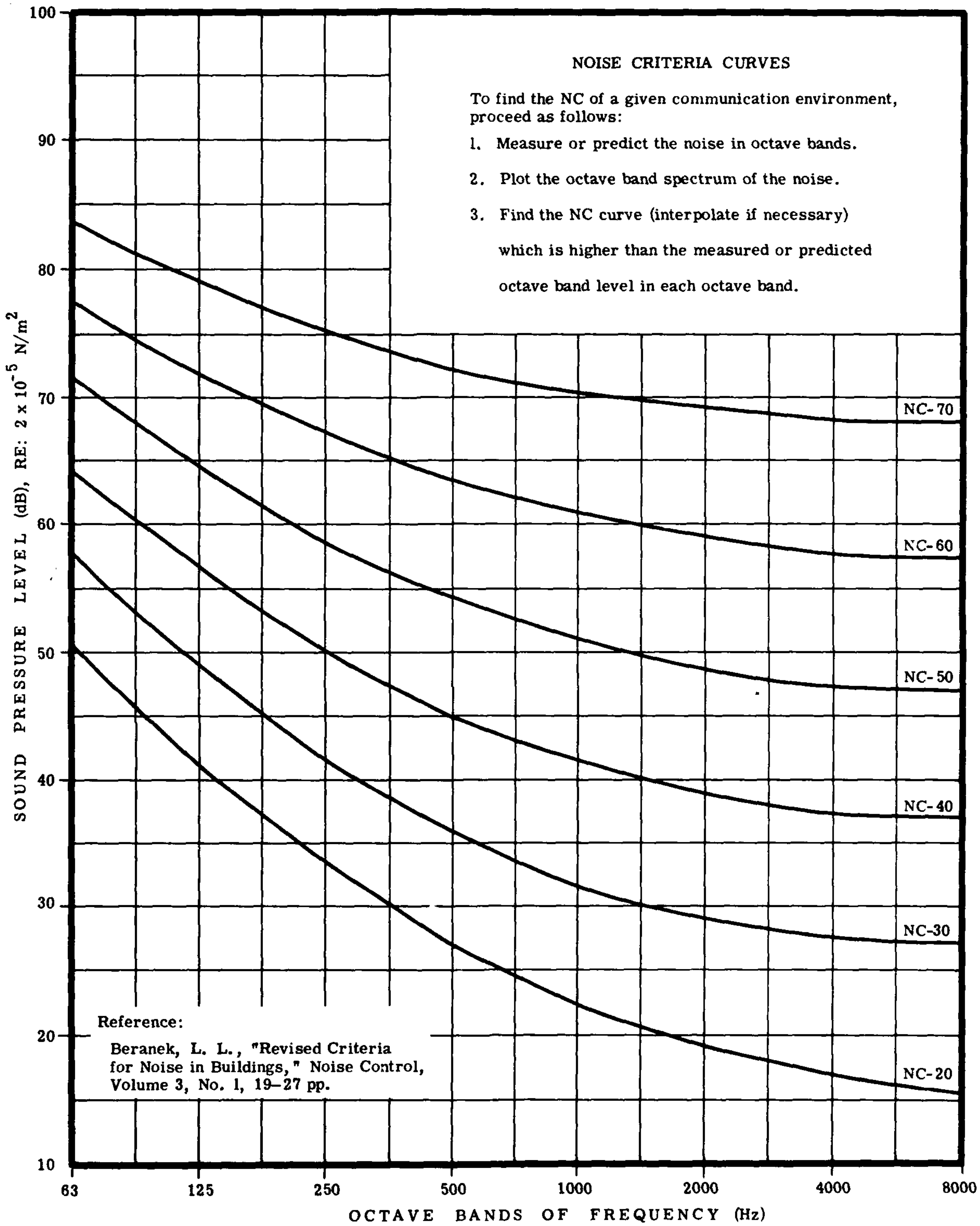


Figure 7-28 Noise Criteria Curves

band is well above the NC-70 criterion while for the 125 Hz band it is just below the NC-70 criterion—the data shown would indicate slight difficulty in communicating, at a raised voice level, when speakers are separated by a distance of three to six feet. Here, once again, the significance of the interference is questionable because the duration of the interfering sound exposure is quite short. The 29 February 1968, change 1, to reference 12 gives data on the sound field at a location 103,962 feet from the launch site. The octave band pressures are: 63 Hz band—76 dB; 125 Hz band—73 dB; 250 Hz band—68 dB; and the 500 Hz band—67 dB. These pressures are near the NC-60 criterion, but there are no data for frequencies above 500 Hz so it is difficult to estimate levels in the critical bands of 1000 and 2000 Hz. However, they should be lower than the 500 Hz band. A best estimate is that conditions are equivalent to criterion NC-60—slight difficulty, raised voice; 3—6 feet. Other operations associated with the manufacture, handling and installations of chemical rocket propulsion systems may produce high level sound fields. The sources will be machinery, and other sources, rather than the rocket engines. The communications criteria of Figure 7-28 and Table 7-3 may be used to assess the quality of voice communications to be expected in all such areas, once the sound fields have been measured. That is, these criteria are applicable to all industrial environments—in fact they are more directly applicable where the noise is present almost continuously during the working period.

7-3.2.2 Potential Hearing Impairment (Hearing Conservation). The frequency region from 100 Hz–6300 Hz includes the entire band of frequencies for which a reduction in the human ear's detection sensitivity decreases man's capability to carry on everyday conversation, either at work, at home or when engaged in recreational activity. Current procedures for predicting the expected impairment for hearing speech signals, usually discount the lower frequency bands, below the octaves centered on 250 Hz. Likewise, the bands centered on frequencies above 4000 Hz are not used in estimating hearing impairment for conversational speech sounds of the English language. In fact, the average hearing threshold level in dB for the three pure tone test frequencies, 500, 1000 and 2000 Hz is the value used in estimating hearing impairment for speech by the most widely employed current method. These facts are pointed out to provide assurance that the criteria to be described adequately cover the frequency range that is essential to assessing hearing impairment for speech signals. It is well established that exposure to industrial sound fields may impair the hearing organs when the octave band pressure levels are high enough and when the exposed work men spend sufficient time in these sound (noise) fields. The basic exposure times are a nominal 8 hours each day, five days each week over the particular working period in years that is under consideration. Where the exposures are different, for example, a series of short exposures repeated a few times each day, the criteria are tentative estimates of the acceptable sound pressure levels and durations of exposure. These tentative criteria are currently under review and perhaps revisions will be made in the next two to five years. Selected criteria, deemed most relevant to the work with the systems being considered are presented below.

7-3.2.2.1 Criteria—Potential Hearing Impairment. The basic criteria are shown in Figure 7-29 (from reference 33) as damage risk contours for one continuous exposure during an 8-hour work day. The contour requiring the lowest band pressure levels is marked 480 min—a full 8-hour period. The pressure levels on the left ordinate are for octave bands and those on the right ordinate are for 1/3-octave bands, all bands centered on the frequency selected from those shown on the abscissa. These levels are considered to be compatible with retention of unimpaired hearing for conversational speech after exposure at work over a total period of more than ten years. The data from Figure 7-29 and the data upon which the figure was based have been used in computations to derive a numerical value of the sound levels that one would expect to measure using a sound level meter equipped with a special filter network, known as the A-Weighting network. This computation gives the A-weighted sound pressure level. The same criteria (in general) are shown in Figure 7-30 as "equivalent" A-weighted sound levels in dB (ordinates) versus exposure time from 1—480 minutes (abscissa) for each work day. Working exposure in years and other related factors are the same as for Figure 7-29. The plotted level values are for summations of different numbers of bands, as shown on the figure. Note that when all bands from 250 Hz–8000 Hz are involved in the summation the highest A-weighted sound level is obtained. The "?" beside some points means that these values were estimations—made because the original curves were cut off at a band pressure level of 135 dB. The A-weighted sound levels are presented because the present trend is toward the use of sound levels expressed in A-weighted values for revising criteria for potential hearing impairment from exposure to industrial noise (sound fields).

7-3.2.2.2 Application—Potential Hearing Impairment Criteria. In regard to the operation of large chemical rocket propulsion systems and other systems (space vehicles, missiles) of which they form a part, the protective structures required for prevention of explosion and blast hazards were considered to attenuate the sound fields below the pressure levels specified by the voice communications criteria. Since the communications criteria impose lower sound levels than do the potential hearing impairment criteria, no risk of hearing impairment is expected. Now, compare the sound field shown in Figure 7-22 (15,000 ft from the launch site)—the 3-minute exposure curve allows an 18 dB higher level at 100 Hz and a 35 dB higher level at 1000 Hz. In fact, the criteria for an exposure duration of 15 minutes are well above the actual band pressure levels shown in Figure 7-22. Since these exposures are usually much shorter than 15 minutes and usually are separated by, at least, several (8 or more) hours no risk of impairment of the hearing organ is expected.

Although no specific data can be supplied, there have been problems of hearing damage potential reported for supporting equipment in varied facilities provided for the operation of chemical rocket propulsion systems. These sources of high level sound fields are mechanical equipment items, such as electric power generators, ventilating systems and other. The criteria given will provide guidance as to acceptable sound levels, expressed either as band pressure levels (octave and 1/3

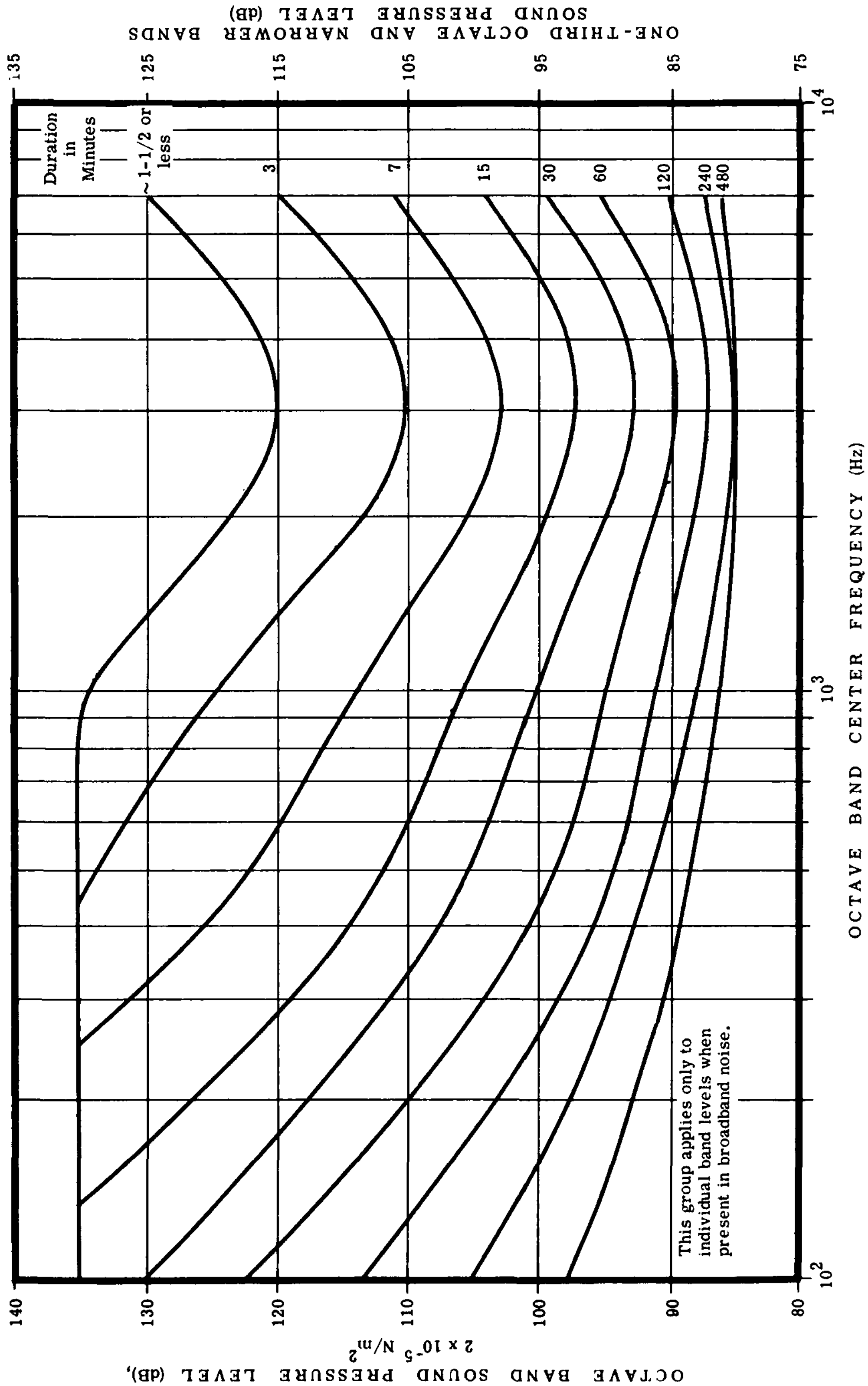


Figure 7-29 Damage Risk Contours for One Exposure Per Day to Octave Bands of Noise

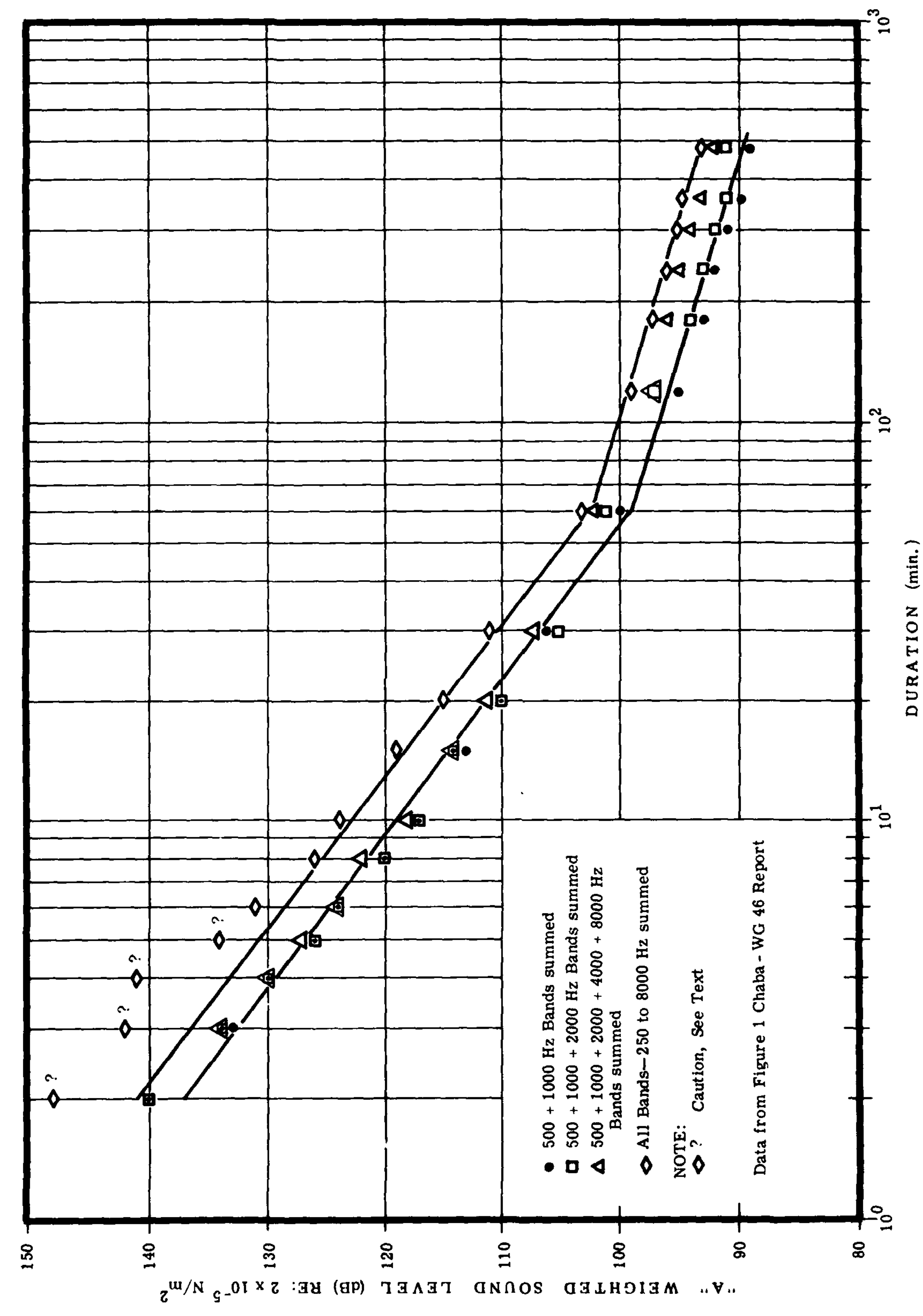


Figure 7-30 Damage Risk Contours of Chaba Converted to Equivalent "A" Weighted Sound Level, (dB)

octave) or as equivalent A-weighted sound level and the corresponding allowable daily exposure time. If each exposure is short but repeated several times daily, reference 32 should be consulted for procedures that may be used. For any specific exposure time shown in Figure 7-29 one may obtain from Figure 7-30 the equivalent acceptable sound level, A-weighted, by reading the sound level value corresponding to the time interval portrayed by the curve selected from Figure 7-29. Interpolation will be necessary for other exposure times, but this should not create significant problems. It is recommended that the value from Figure 7-30, selected for use, be that midway between the two curves drawn on the figure.

These same criteria for potential hearing impairment are applicable to the sound fields (noise) found in the varied industrial plants and facilities concerned with manufacture of components and production of chemical rocket propulsion systems. In general, the criteria given apply to situations in which no ear protection or other hearing conservation measures are in effect. If the criterion sound levels are exceeded, hearing conservation procedures are required and these procedures are discussed later in this chapter. (Section 7-4.2.1)

7-3.2.3 Community Disturbance (Annoyance). Sounds generated by industrial plants and transportation systems, particularly aircraft in operation on the ground and in flight at low and medium altitudes, frequently propagate into residential areas of the communities that are adjacent to them, or in the case of aircraft, beneath the flight paths. The intrusion of these sound fields into the community environment may arouse annoyance among the community residents and lead to a variety of actions directed toward the removal of the sound fields, which usually means toward cessation of the sound generating operations. This problem area is manifested in connection with the operation of chemical rocket propulsion equipment and the systems they propel. The responses or reactions of the community residents, either as individuals or as groups, are extremely complex both with respect to the factors making up the final stimulus and those contributing to the formation of the final response. This potential problem associated with rocket propulsion system operations will be approached herein by citing significant approaches used where aircraft were the sound sources. An early approach to this problem area, made in 1952, is described in reference 34. It was primarily related to military aircraft operations. A further elaboration of this methodology was outlined in reference 35 (1955). A modification of these methods aimed primarily toward making the computational tasks easier was published in 1957 (reference 36). This was an Air Force document dealing with procedures for estimating the noise exposure to communities and their probable response to noise from air operations. Later in 1957 the methodology of reference 36 was modified to make it suitable (to the maximum extent) for handling like problems associated with missile operations (reference 37). This was a method for assessing noise from missile static firing and launch sites and the resultant community response and remains the only method oriented specifically to these particular problems. It is suggested that the methodology of reference 37 may be used—and it will have to be applied specifically to each operation or installation. However, the parts of this chapter which describe methods for estimating sound fields (in the far field) from static firings and from launch operations provides octave band sound pressure data for many distances and directions from the source. Those desiring estimates of possible community response may desire to start with the procedures given in reference 38, which uses perceived noisiness to assess the judgments people make about a noise (sound field) around them. In this case it will be necessary to develop an entirely new set of assessment tools but the references given will serve to guide this development. No attempt has been made to develop these methods for community response to sound fields from rocket engines, but for aircraft noise the development process is in full swing and changing daily—hence no detailed methodology based on perceived noisiness or computed estimates of perceived noisiness are given herein.

It should be pointed out that this frequency band, particularly that segment below 500 Hz, may reach residential areas outside the facility boundaries at sound pressure levels high enough to excite vibrations in components and furnishings of dwellings. However, these frequencies will attenuate more than those discussed earlier in this chapter (from 1–100 Hz). Experience will have to determine whether earlier procedures for estimating community response do actually include and take account of these effects on residential structures.

7-3.3 HIGH FREQUENCY SOUND (NOISE)—6300–20,000 Hz. This frequency region is still in the audible (audio) range, although many persons, older than age 40, will not hear these frequencies. No communication criteria exist for this part of the spectrum because its contribution to understanding speech signals is negligible. Likewise these frequencies are of little importance for current methods of evaluating potential hearing damage and no criteria exist. Although the octave band pressure levels of this frequency span may be rather high very near the launch or test pad, they are attenuated sharply by the protective structures, required for other reasons, and therefore are considered of no importance, even as agents which may evoke annoyance responses. On propagation over the distances between the test or launch site and the facility boundaries they are attenuated sharply and are below levels of any significance in surrounding community areas. Therefore, no criteria are needed and none have been developed.

7-3.4 ULTRASOUND—FREQUENCIES ABOVE 20,000 Hz. The sounds of this frequency region are called ultrasound because they are nominally higher in frequency than the high frequency detection limit of human ears. It is known that the sound fields of chemical rocket propulsion systems do contain frequency components from 20,000 Hz up to at least 150,000 Hz. All these frequencies are strongly attenuated on propagation through air and by all the material used in the construction of typical buildings and, as a result, are not present in work area or residential environments at pressure level high enough to exert any deleterious action on man. There appears to be no need for criteria pertaining to their effects on man and none are given.

7-4 PLANNING IN RELATION TO ACOUSTIC ENERGY FIELDS

Airborne sound waves (acoustic energy fields) spread out from any source and deliver acoustic energy at relatively high levels into work areas and into residential or business areas outside the boundaries of the sound producing operations. The actual energy levels in either the work areas of the facility or the surrounding residential or business areas depend on the particular source energy level and the distance that separates the particular area under consideration from the acoustic energy source. The propagated acoustic energy may create sound fields in the work environments or in the residential/business environments that are incompatible with the functions people must carry out in these areas. Since chemical rocket propulsion systems and the factories that produce them or their component parts and materials are likely to be sources of high level acoustic energy, the control of this energy must be considered in planning all operations, procedures and facilities associated with their production and operation. These essential planning actions may be separated into two (2) groups: (1) facility planning actions and (2) operations planning actions. These essential planning actions are the subject of this section of Chapter 7.

7-4.1 FACILITY PLANNING. The facility planning problems will vary with the particular type of facility and operation under consideration. The plants for manufacture of parts, components or materials and the assembly of these into chemical rocket propulsion systems will usually present different problems than are encountered in planning a facility for the test or operational use of these propulsion systems. However, the same general types of problems will be encountered for all of these facilities and these are: problems related to site selection; problems related to facility layout; and problems related to appropriate land use. References 39, 40, and 41 will provide guidance for the solution of problems associated with planning the manufacturing operations and the material in Section 7-2 of this chapter and the references cited therein will provide guidance for problems associated with planning for the operation of the propulsion systems.

7-4.1.1 Site Selection. The problems related to site selection are primarily concerned with the effects of the sound fields outside the facility and where the sound levels are very high the effects imposed upon on-facility buildings and other structures that may determine separation distances from the source and thereby the total area of the site. These site selection problems are considered separately for manufacturing sites and test/operation sites.

7-4.1.1.1 Manufacturing Facility Siting. Here only facilities (or their sites) are considered that are not used to test large chemical rocket propulsion systems. These facilities are assumed to be similar to commercial manufacturing facilities in general and it will be a rare occasion on which the sound fields determine separation of manufacturing units. The actual site selection will be influenced by the sound fields only to the extent of assuring sufficient distances from the sound sources to facility boundaries to assure minimal effect on human activities outside the controlled area of the facility. It is important that this problem not be overlooked and guidance can be found in References 39, 40, and 41. The criteria for voice communication may be useful in specifying the sound levels at the facility boundary. If ground area is limited, it may be necessary to apply noise control treatments and designs to certain operations and machinery installations.

7-4.1.1.2 Test or Operation Sites. Facilities to be used for test (restrained) operation and launch operation of chemical rocket propulsion systems, particularly the large systems used for space operations will be subjected to very high level sound fields. The major problems on site selection are, to obtain sufficient land area to separate test and/or launch pads sufficiently to avoid structural damage at one operating site by the sound fields generated at a neighboring site; and to assure that operating sites (test or launch) are sufficiently separated from the boundaries of the entire facility to avoid adverse effects on people and activities carried on in areas adjacent to the facility. Examples were given in the discussions of the application of criteria, earlier in the chapter, that can be used to estimate the necessary distances between facility sources and surrounding neighbors. Each facility must be evaluated separately, taking into account the acoustic energy output of the sources, the durations of each operation and the time intervals between each successive operation. In general large areas are required and these facilities should be surrounded by areas of low population concentration, if possible.

7-4.1.2 Facility Layout. In the layout of manufacturing facilities the primary considerations are achieving sound levels that are compatible with essential voice communications for each operation (see application of communication criteria) and assuring adequate protection for the hearing organs of personnel (see application of potential hearing impairment criteria). Operations that produce high level noise fields should be isolated to the maximum extent compatible with production sequences to minimize adverse effects of sound (noise) on personnel.

In the layout of test or operational sites primary consideration must be given to the provision of adequate personnel protection and maintaining sound levels at support equipment installations that assure their continuous normal operation. Usually these objectives are achieved by maintaining adequate separation distances between the sources and personnel or sensitive equipment installations. Personnel protection is also achieved by housing them in specially designed protective buildings. Frequently the requirements for protection for potential explosion blast waves automatically assure adequate soundwave exclusion for personnel protection.

7-4.1.3 Land Use. Land use, here, refers primarily to the use of land adjacent to any of the facilities as sites for supporting functions or related operations that produce less noise. Where this is possible the resident users of the surrounding community areas are afforded additional protection from the sound fields by the larger separation distances.

7-4.2 OPERATIONS PLANNING. Once the general plan for a facility, including the choice of site and the preliminary layout sketch, is completed, a plan for the operations to be carried out must be formulated. Several factors associated with the operations, and made evident by the operations plan, can influence the final layout and the size range of propulsion systems and the frequency of their operations will be of major importance in assuring inside-facility protection of operating personnel from the intense sound fields. These same factors must also be considered in solving outside-the-facility problems created by the high level sound fields propagated through air from the sources operated within.

7-4.2.1 Inside-the-Facility Planning. Within the facility the major problems may be associated with control of sound levels (noise levels) so that they are low enough to permit adequate voice communication. All critical operational areas must be assessed in terms of the sound levels compatible with the necessary quality of voice communications (see criteria given earlier in this chapter). Attention must be given to the sound fields generated by internal support equipment. Frequently where special control houses or rooms are in use, these sound fields interfere with communication to a larger extent than do the propulsion unit sound fields.

The second problem created by sound fields inside the facility is potential hearing impairment by exposure to operating sounds. The allowable levels are higher than those required for adequate communication (see criteria for potential hearing impairment). However, all phases of the operation must be studied—and a determination made, on the basis of estimated noise levels, of the actual hazards to hearing that may be expected. Should these studies show the existence of a potential hazard to the hearing organs—an explicit, detailed hearing conservation program should be planned and instituted when operations start. The hearing conservation program plan must be formulated under competent medical supervision and will include monitoring audiometry, use of earplugs, earmuffs and other protective equipment. If these measures do not assure elimination of the hazard special noise reduction structures may be installed and a controlled work program, limiting the exposure time may also be employed. Owing to the likelihood of most longer exposure durations the hazards to hearing may be a major problem at industrial facilities. The criteria are the same for all types or classes of facilities.

7-4.2.2 Outside-the-Facility Planning. Assuming that facilities are located initially on a sufficiently extensive land area to assure appropriately low sound levels at its boundaries, the primary problem will be to control operations so that excessively high noise levels in the surrounding communities are avoided under unusual meteorological conditions. The problems related to community response to noise are discussed in the section on community disturbances. Based on this guidance the local meteorological patterns must be studied for each installation so that operations can be scheduled to avoid periods when unusually high sound levels are predicted for surrounding communities. The extremely low frequencies generated by the larger propulsion systems may be the sources of most community disturbance by exciting vibrations and thereby secondary sound fields in residential structures, their finishing and their contents. The potential for this type of disturbance must receive major consideration in planning the overall operation of any facility.

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13. ABSTRACT

(U) This joint Army, Navy, NASA, Air Force manual provides general guidance safety criteria, procedures, instructions, precautions, and related technical information as assistance to those persons responsible for minimizing the hazards associated with the operation of propellant handling and motor and engine test facilities by the services or NASA.

(U) Seven chapters cover the facility aspects of planning a safe operation irrespective of the particular propellant involved.

(U) Useful guidelines are given for controlling or minimizing toxicity, fire, and explosion hazards. Extensive coverage for blast hazards includes nomographs for estimating blast overpressures, providing that TNT equivalence (and geometry) can be shown for the desired system.

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Hazard Identification						
Hazardous Materials						
Propellant Blast Effects						
Propellant Disposal						
Propellant Fire Hazards						
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Safety Design Criteria						

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